LDRP97 Multi-Hazard Analysis

Christchurch City Council

Gap Analysis Report

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Contents

Executive Summary

Christchurch City Council (Council) is undertaking the Land Drainage Recovery Programme in order to assess the effects of the earthquakes on flood risk to Christchurch. In the course of these investigations it has become better understood that floodplain management should be considered in a multi natural hazards context. Council have therefore engaged the Jacobs, Beca, University of Canterbury, and HR Wallingford project team to investigate the multihazards in eastern areas of Christchurch and develop flood management options which also consider other natural hazards in that context (i.e. how other hazards contribute to flooding both through temporal and spatial coincidence). The study has three stages:

- Stage 1 Gap Analysis – assessment of information known, identification of gaps and studies required to fill the gaps.
- Stage 2 Hazard Studies – a gap filling stage with the studies identified in Stage 1.
- Stage 3 Collating, Optioneering and Reporting – development of options to manage flood risk.

This present report is to document findings of Stage 1 and recommends the studies that should be completed for Stage 2. It has also been important to consider how Stage 3 would be delivered and the gaps are prioritised to provide for this.

The level of information available and hazards to consider is extensive; requiring this report to be made up of five parts each identifying individual gaps. A process of identifying information for individual hazards in Christchurch has been undertaken and documented (Part 1) followed by assessing the spatial co-location (Part 2) and probabilistic presence of multi hazards using available information. Part 3 considers multi hazard presence both as a temporal coincidence (e.g. an earthquake and flood occurring at one time) and as a cascade sequence (e.g. earthquake followed by a flood at some point in the future). Council have already undertaken a number of options studies for managing flood risk and these are documented in Part 4. Finally Part 5 provides the Gap Analysis Summary and Recommendations to Council.

The key findings of Stage 1 gap analysis are:

- The spatial analysis showed eastern Christchurch has a large number of hazards present with only 20% of the study area not being affected by any of the hazards mapped. Over 20% of the study area is exposed to four or more hazards at the frequencies and data available.

- The majority of the Residential Red Zone is strongly exposed to multiple hazards, with 86% of the area being exposed to 4 or more hazards, and 24% being exposed to 6 or more hazards.

- A wide number of gaps are present; however, prioritisation needs to consider the level of benefit and risks associated with not undertaking the studies. In light of this 10 studies ranging in scale are recommended to be done for the project team to complete the present scope of Stage 3.

- Stage 3 will need to consider a number of engineering options to address hazards and compare with policy options; however, Council have not established a consistent policy on managed retreat that can be applied for equal comparison; without which substantial assumptions are required. We recommend Council undertake a study to define a managed retreat framework as an option for the city.

- In undertaking Stage 1 with floodplain management as the focal point in a multi hazards context we have identified that Stage 3 requires consideration of options in the context of economics, implementation and residual risk. Presently the scope of work will provide a level of definition for floodplain options; however, this will not be at equal levels of detail for other hazard management options. Therefore, we recommend Council considers undertaking other studies with those key hazards (e.g. Coastal Hazards) as a focal point and identifies the engineering options to address such hazards. Doing so will provide equal levels of information for Council to make an informed and defendable decision on which options are progressed following Stage 3.

Important note about your report

The sole purpose of this report and the associated services performed by Jacobs is to assess Gaps in information on hazards associated with flooding in eastern Christchurch in accordance with the scope of services set out in the contract between Jacobs and Christchurch City Council ('the Client'). That scope of services, as described in this report, was developed with the Client.

In preparing this report, Jacobs has relied upon, and presumed accurate, any information (or confirmation of the absence thereof) provided by the Client and/or from other sources. Except as otherwise stated in the report, Jacobs has not attempted to verify the accuracy or completeness of any such information. If the information is subsequently determined to be false, inaccurate or incomplete then it is possible that our observations and conclusions as expressed in this report may change.

Jacobs derived the data in this report from information sourced from the Client (if any) and/or available in the public domain at the time or times outlined in this report. The passage of time, manifestation of latent conditions or impacts of future events may require further examination of the project and subsequent data analysis, and re-evaluation of the data, findings, observations and conclusions expressed in this report. Jacobs has prepared this report in accordance with the usual care and thoroughness of the consulting profession, for the sole purpose described above and by reference to applicable standards, guidelines, procedures and practices at the date of issue of this report. For the reasons outlined above, however, no other warranty or guarantee, whether expressed or implied, is made as to the data, observations and findings expressed in this report, to the extent permitted by law.

This report should be read in full and no excerpts are to be taken as representative of the findings. No responsibility is accepted by Jacobs for use of any part of this report in any other context.

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Abbreviations

Abbreviation	Explanation
AEP	Annual Exceedance Probability
CES	Canterbury Earthquake Sequence
CERA	Canterbury Earthquake Recovery Authority
CRPS	Canterbury Regional Policy Statement 2013
CWMS	Canterbury Water Management Strategy
CDB	Christchurch Drainage Board
CDP	Christchurch District Plan
CRDP	Christchurch Replacement District Plan
FPCWAMP	Christchurch City Council Flood Protection and Control Works Activity Management Plan
SDAMP	Christchurch City Council Stormwater Drainage Activity Management Plan
CDEM	Civil Defence and Emergency Management Act 2002
CMA	Coastal Marine Area
CHRM	Community Housing Redevelopment Mechanism
CSNDC	Comprehensive Stormwater Network Discharge Consent
EDM	Enhanced Development Mechanism
EQC	The Earthquake Commission
ENSO	El Nino Southern Oscillation
FMFLO	Fixed Minimum Floor Level Overlay
FMA	Flood Management Area
FPMA	Flood Ponding Management Areas
HAT	Highest Astronomical Tide
HFHMA	High Flood Hazard Management Area
IHP	Independent Hearings Panel
IPO	Interdecadal Pacific Oscillation
ISQG	Interim Sediment Quality Guidelines
LDRP	Land Drainage Recovery Programme
LURP	Land Use Recovery Plan
LGA	Local Government Act 2002
LTP	Long-term Plan 2015-25
MHRA	Multi-Hazard Risk Assessments
NZCPS	New Zealand Coastal Policy Statement
ODP	Outline Development Plan

Abbreviation	Explanation
RMD	Residential Medium Density
RS	Residential Suburban
RSDT	Residential Suburban Density Transition
RMA	Resource Management Act 1991
SMP	Stormwater Management Plan
SWAN	Simulating Waves Nearshore
SWASMP	South West Area SMP
UDS	Greater Christchurch Urban Development Strategy
SWCAP	South-West Christchurch Area Plan
WWDG	Waterways, Wetland and Drainage Guide
ZIP	Zone Implementation Programme

1. Introduction

1.1 Project Context

The Canterbury earthquake sequence starting in September 2010 has caused large amounts of damage and ground changes across Christchurch. As further assessments have been undertaken within various earthquake recovery programmes by organisations including Christchurch City Council (Council), Stronger Christchurch Infrastructure Rebuild Team (SCIRT), Canterbury Earthquake Recovery Authority (CERA) and the Earthquake Commission (EQC), the effects of the earthquakes are becoming better understood; particularly for consequential risk changes for other hazards in Christchurch.

The key hazard of focus in the present study is flood risk which is being investigated within the Land Drainage Recovery Programme (LDRP) by Council. The LDRP was established to assess and reinstate the pre-earthquake levels of service to Christchurch for flood risk. A number of projects have been completed with flood risk as a focal point and have identified a range of options to return levels of service. As more information has come to light it has been identified that a number of associated hazards and consequential changes may affect flood risk to land, and that other hazards combined with flood risk may affect land tenure if not considered holistically. Council has identified this need in the context of floodplain management and has engaged a project team led by Jacobs consisting of Beca, University of Canterbury and HR Walllingford to investigate this further.

Hazards included in this study are:

- extreme weather events,
- coastal erosion and inundation,
- tsunami,
- earthquake and liquefaction,
- groundwater change,
- regional flood (Waimakariri River); and
- hill slope instability

1.1.1 Project Objectives & Focus

The project objectives are to develop flood management plans for the study areas, involving developing a range of sustainable, adaptable and resilient flood management options including engineering, planning and policy responses. The study areas are the lower catchments of the Styx, Avon and Heathcote Rivers along with the coastal margins of Ihutai/Avon-Heathcote Estuary and Sumner. The Conceptual Model shown in **Figure 1-1** demonstrates all of the components that we have been asked to consider in the development of Flood Management Plans.

In the context of this project there is a need to account for the influences of other natural hazards and long term changes (e.g. climate change) on the magnitude, frequency and extent of the flooding as well as on the development of sustainable and resilient mitigation options. In undertaking a multi-hazard approach to the flood management planning, it is the spatial co-location, temporal coincidence and cascading impacts of the hazards that are also being assessed. Within this report these terms have the following definitions:

- Spatial Co-location: The possibility of two or more hazards affecting the same spatial location regardless of the frequency of the hazards or the period of time between individual hazard events.

- Temporal Coincidence: The possibility that two hazard events can occur at the same time and in the same location. In the context of this study, it is the co-incidence of non-flood hazards with flooding events that is of interest.

- Cascading: The occurrence of one hazard event, followed some time later by a second type of hazard event, whereby the first hazard occurrence has altered some geomorphologic or other condition to such a degree that the second hazard event is either exacerbated or even triggered. In the context of this study, we are interested in when non-flood hazards affect the likelihood or nature of future flooding hazard events.

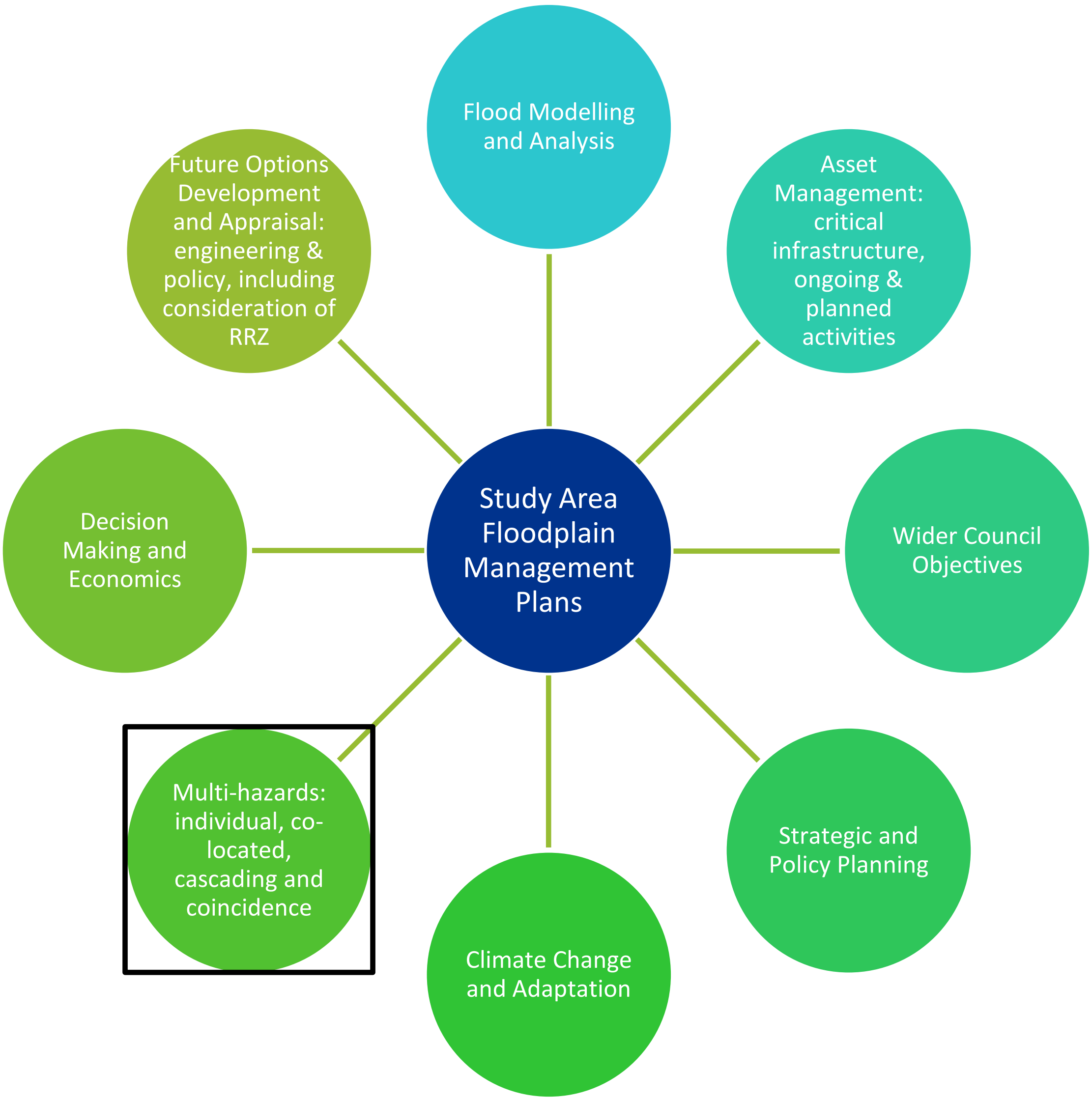

Figure 1-1 Conceptual Model of components to be considered with the floodplain management plans with box indicating the focus of the present report. Boxed multi-hazards circle (bottom left of diagram) represents the model component that is the focus of this report. See above for definitions of co-located, cascading and coincidence.

1.1.2 Project Methodology

The project is defined by three stages as summarised below with **Figure 1-2** showing the project approach being used to develop these stages:

1. Gap Analysis: A review of previous studies and international literature to identify gaps in options considered to date, non-flood hazards and other information which may be needed to inform Stage 3. Gaps found will be considered by Council to be addressed in Stage 2.

2. Hazard Studies: Stage 2 is undertaking the studies identified in Stage 1 agreed as being required to fill the gaps on multi-hazard spatial co-location, temporal coincidence and cascading impacts, along with other gaps on existing engineering infrastructure, planning and policy directions, which will allow the development of sustainable and resilient flood mitigation options in stage 3.

3. Collating, Optioneering and Reporting: This stage has a focus of developing options (both policy and engineering) informed by the information collated in Stage 1 and developed in Stage 2. The options are to be focused on flood plain management but also consider how other hazards may be addressed within these options.

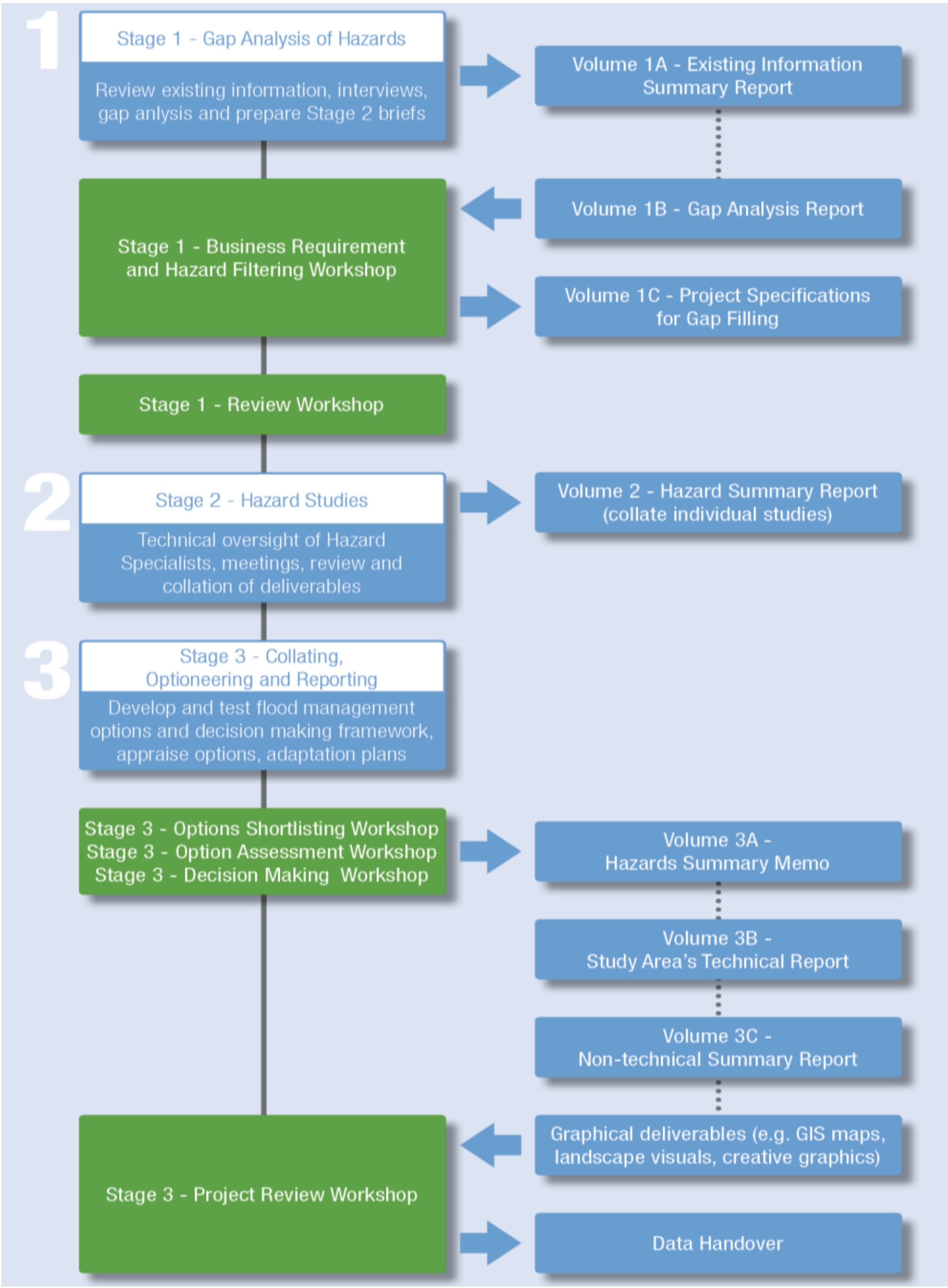

Figure 1-2 Project Approach

1.2 Scope of this Report

This report is to address Stage 1 as summarised above. In undertaking this multi-hazard approach, this report involves assessing the gaps in knowledge of the likelihood and consequences of the individual hazards and long term changes and determining which multi-hazard interactions, by either spatial co-location, temporal coincidence or cascading of events exacerbate flood magnitude, frequency and/or extent. The results of this initial first pass assessment of individual and multi-hazard interactions will be workshopped with the Project Advisory Group.

The first stage then moves to identify the gaps in knowledge on the multi-hazard occurrence and the nature of process-response interactions that are required to be addressed before the multi-hazards can be considered in the assessment of flood mitigation options along with all the components of preparing the floodplain management plan for the study areas.

Also included in the Stage 1 Gap Analysis is a high level stock-take of information on existing hazard mitigation infrastructure, existing planning mechanisms and policy measures to address flood risk, and proposed Residential Red Zone (RRZ) and other council projects to assess knowledge gaps that may need be to be addressed before a Flood Management Plan can be developed.

1.3 Report Structure and Summary

This report is structured in five parts:

1. Non-Flood Hazard Events Gap Analysis: A review of non-flood hazards; their process-response interactions that are relevant to Christchurch flood hazards; the information, data and modelling availability; and the limitations in this information and modelling which influences our knowledge on their potential impacts on the flood hazards within the city.

2. Multiple Hazard Spatial Co-location Gap Analysis: Analysis of spatial data sets of all natural hazards to determine where we have gaps in knowledge about the spatial co-location of multiple hazards.

3. Multi-hazard Co-incidence and Cascading Gap Analysis: Identification of the key gaps in knowledge about the process-response interactions and consequences between non flood and flood hazards resulting from co-incidence or cascading of the hazards.

4. Engineering and Planning Response Gap Analysis: Identification of the gaps in knowledge or information on existing engineering and planning mitigation measures for flooding, and their effectiveness for providing effective mitigation within a multi-hazards framework.

5. Gap Analysis Summary and Recommendations: A summary of gaps found with recommendation for those to be filled during Stage 2 of this project. We have also provided an outline of any further considerations to be made for Stage 3.

2. Study Areas

The project study area is broken into four based on the fluvial and pluvial floodplains. These are the lower catchments of the Styx, Avon and Heathcote Rivers along with the coastal margins of Ihutai/Avon-Heathcote Estuary and Sumner (labelled as Southshore & Estuary) and are shown in **Figure 2-1**. The upper limit of each of these areas was set by Council at the assumed upper limits of coastal multi-hazard risk, taken at this stage to be the limit of tidal influence on flood levels.

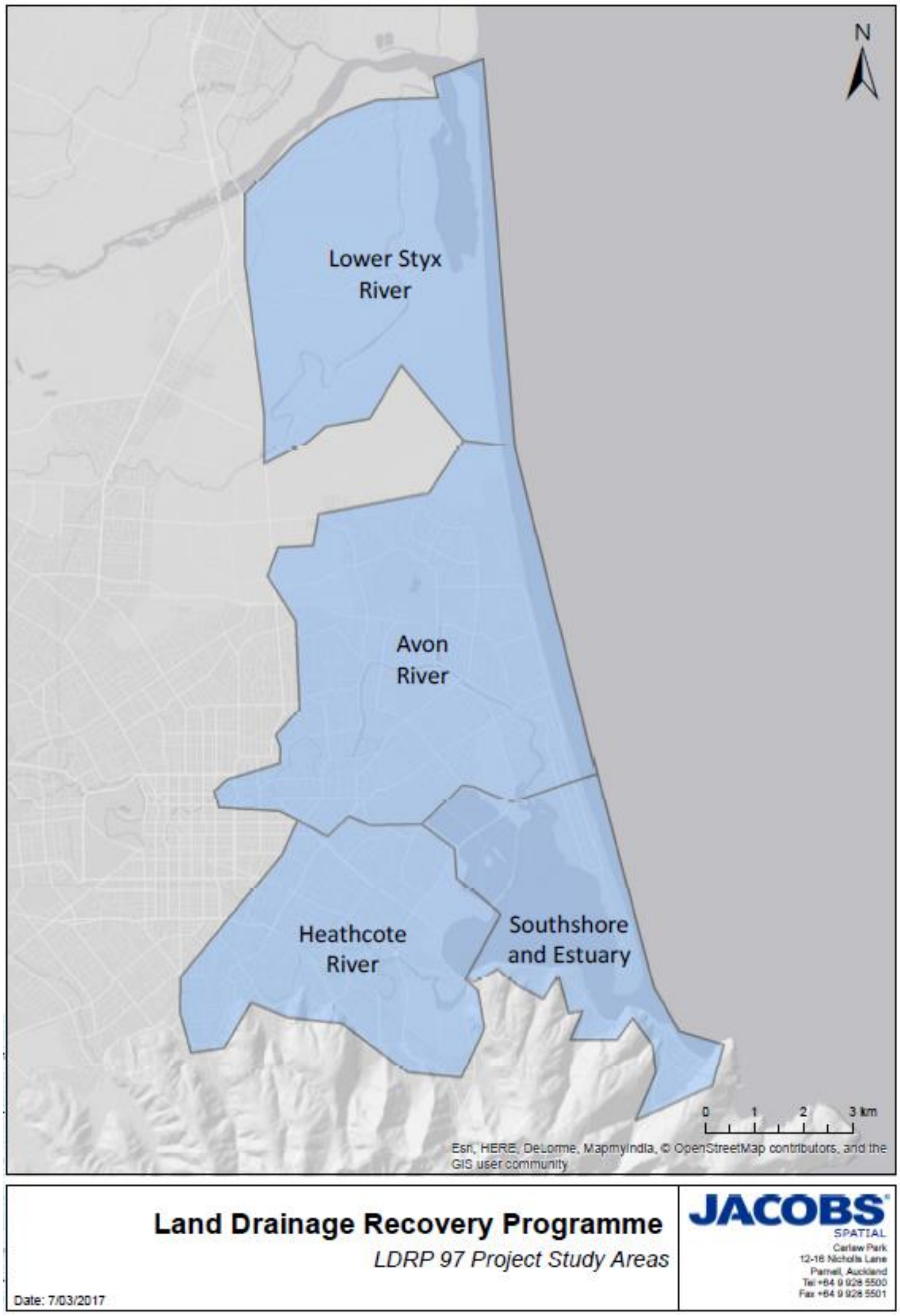

Figure 2-1 LDRP97 Project Study Areas

3. Overview of Multi-hazard Approach

3.1 International Literature Review

The literature commonly divides natural hazards are divided into five hazard groups of;

- Geophysical (earthquake, tsunami, volcanic eruption, landslide, snow avalanche),
- Hydrological (flood, drought),
- Shallow Earth Processes (regional and local subsidence and uplift, erosion, mass movement),
- Atmospheric (severe wind, hail, snow, lighting, thunderstorms, long-term climate change), and
- Biophysical (wildfire).

In the past it has been common that a natural hazards risk approach deals with just one of these hazards or hazard groups and assesses the vulnerability of human use systems to that hazard. In comparison, a multi-hazard risk approach combines multiple hazard sources and multiple vulnerable elements coinciding in time and/or space (Carpignano et al., 2010), with the existing international research on hazard interaction in Multi-Hazard Risk Assessments (MHRA) mainly focusing on the domino (cascade) effect, whereby one hazardous event triggers another (Liu *et al*., 2016). Gill and Malamud (2014) list the other forms of multi-hazard interactions as including; those where the probability of a secondary hazard is increased due to the occurrence of a primary hazard changing the environmental tipping or threshold parameters for the second hazard, those where the probability is decreased, and events involving spatial and temporal coincidence of the natural hazards such that the risk and impacts may be different than the sum of their parts.

Multi-hazard interactions have been recognised in the international natural hazard literature over the last ten years, but the method of application and presentation is still in the process of being developed. So, at the moment there is no international standard approach to multi-hazard analysis (Hart & Hawke 2016), with analysis, vulnerability and risk methodologies varying between different natural hazards and research investigations (e.g. King and Bell 2005; Seville 2008; Smith and Petley 2009; Kappes *et al*. 2012; Gill and Malamud 2014; and Liu *et al*. 2016). However, in general most approaches are either spatially oriented or thematically defined (Kappes *et al*. 2012). This project is primarily thematically defined, as it focuses on fluvial and pluvial flooding as its primary hazard and all other hazards are assessed with respect to their exacerbation of flooding.

A conceptual framework for a multi-hazard approach for moving from a multi-layer single hazard approach to a multi-hazard approach as provided by Gill and Malamud (2014) is presented in **Figure 3-1**.

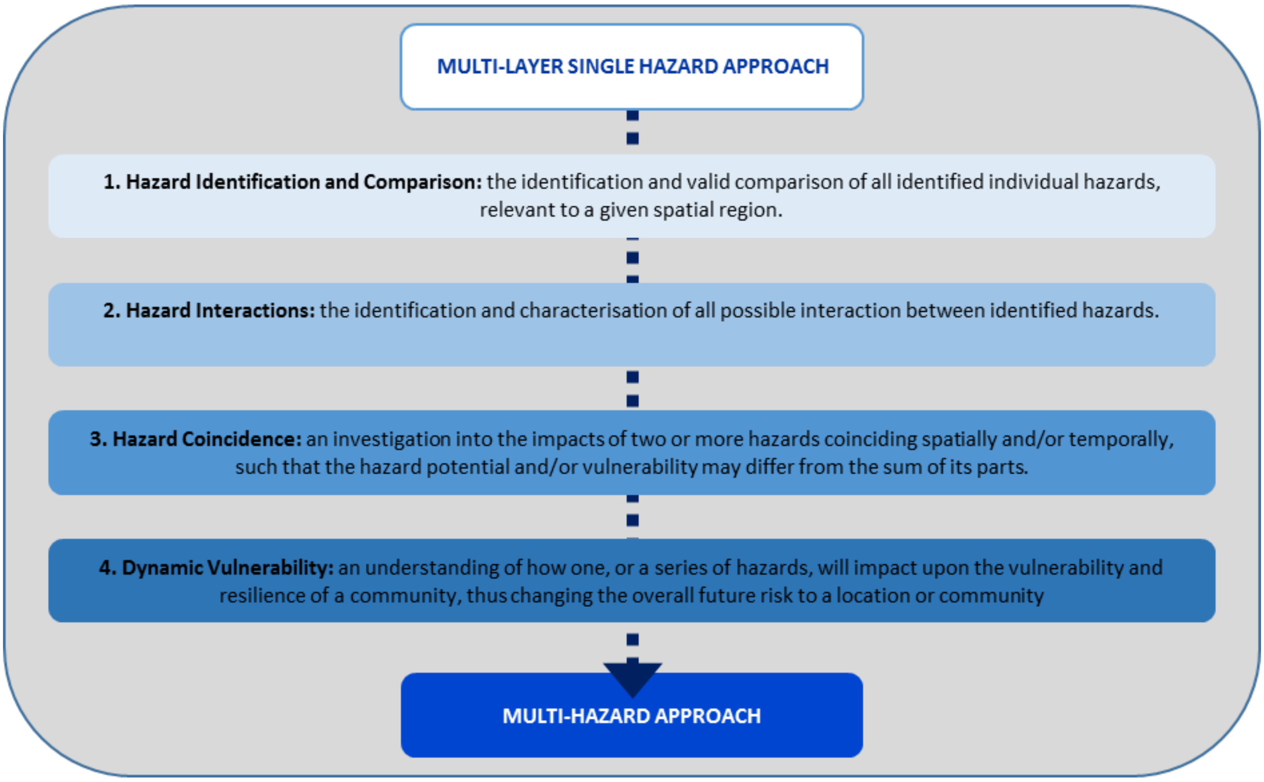

Figure 3-1 A four step Framework for moving from a single hazard to a multi-hazard approach (modified by Hart and Hawke, 2016 from Gill and Malamud 2014, p78)

The steps can be summarised as follows:

- **Step 1 – Single hazard identification and comparison.** This step is relatively straight forward, using a spatially oriented methodology. However, difficulties arise in hazard comparisons since not only do different hazards have different natures, intensities, probabilities and effects on the environment, but their intensities are also measured differently (Carpignano *et al*. 2010). Especially challenging is the use of non-uniform reference units (Kappes *et al*. 2012). This issue can be overcome to some extent by either using a standardising classification technique and/or the development of indices using a continuous or semi-quantitative approach (e.g. Menoni 2006).
- **Step 2 – Hazard interactions.** This step comprises of the identification and characterisation of all possible interactions between the hazards identified in Step 1. It should be noted that as outlined above, in this study only interactions between the fluvial and pluvial flood (FPF) hazard and each of the other hazard events or long term climate changes have been assessed, making it a selective and one-way analysis.
- **Step 3 – Hazard coincidence.** This stage involves the investigation of the impacts of spatial and/or temporal coincidence of two or more hazards. This can be done qualitatively, based on a process focus as presented by Hart and Hawke (2016), or quantitatively as exemplified by Kappes *et al.* (2012). The existing international research on hazard interaction in MHRA mainly focuses on the domino (cascade) effect, whereby one hazardous event triggers another (Liu *et al*., 2016). As outlined above, in the current study the coincidence of cascade effects of hazards is focused on the degree that a primary hazard exacerbates the FPF hazard.
- **Step 4 – Dynamic vulnerability.** Establishes how a series of hazards might impact upon the vulnerability and resilience of a community, and on that community's options for managing the FPF hazard.

A similar multi-hazards framework is provided by Liu *et al* (2016), however, includes a fifth stage of 'visualisation schemes of the hazard risks', which involves a figure or table representing the probability of multiple hazards and corresponding loss. From the international literature, the following most commonly used visualisation schemes of hazard risk included:

1. Qualitative descriptions and classifications: Categorisation of hazard chains by the cause of the hazard, spatial, and temporal parameters. This visualisation is perhaps the least comprehensive of the visualisation schemes, but has merit for high-level analyses due to its adaptability and simplicity.

2. Matrices and diagrams/vulnerability curves: A semi-quantitative approach to visualise hazard interactions and vulnerability of exposed elements. While vulnerability curves derive from accurate analysis of elements that make a given object more or less susceptible to damage, the matrix approach generally relies upon very few parameters (Menoni *et al.,* 2006). As such, matrices are most commonly used as they are more adaptable and can be used for hazards that are more difficult to parameterise.

3. Probability/scenario trees: Visualisation of possible primary and secondary hazards using expert elicitation to assign uncertainty. However, assessing and quantifying the uncertainties associated with each parameter and possible outcomes is a difficult process, and the necessity for multi-disciplinary expertise has resulted in this visualisation scheme being less popular than other schemes.

4. Risk maps: spatial visualisation of risk within the area of interest, utilising a diverse range of methodologies to calculate risk levels. The risk-mapping process remains constrained by a single risk approach and the diversity of the methodologies makes it difficult to compare results (Carpignano *et al*., 2010).

3.2 Christchurch Multi-Hazard Literature Review

Similarly to the international situation, the identification and assessment of multi-hazard interactions in Christchurch has only been recently considered. Previously, studies focused on the identification and understanding of one hazard alone without considering how the hazard interacted with other hazards. Examples include studies of liquefaction potential, rockfall potential and flooding hazards that led to single hazard management responses such as identification of these hazards on specific Land Information Memorandums (LIMs) for houses within mapped hazard zones in Christchurch. Planning controls focused on the individual hazards with no specific consideration of controlling or limiting development in areas subject to multiple hazards (e.g. the suburb of Bexley as discussed Hart et al., 2015).

The impact of the Canterbury Earthquake Sequence (CES) on flood events in Christchurch has been assessed by Allen *et al.* (2014). Shortly after the CESCES the University of Canterbury (UC) worked with the American Society of Civil Engineers Technical Council on Lifeline Earthquake Engineering (TCLEE) to develop an earthquake-flood multi-hazard project to investigate the increased flood risk to Christchurch. The UC-TCLEE international collaboration project on “Earthquake-Flood Multi-Hazard Impacts to Lifeline Systems” was formalized in 2012. UC students and advisors were working with the Christchurch lifeline organizations and community when the 5 March 2014 floods occurred. The Geotechnical Extreme Events Reconnaissance GEER team mobilized to investigate and document the flood events, in support of initiatives such as the UC-TCLEE on-going earthquake-flood multi-hazard investigation efforts.

This study considered that the flood events occurring after the 2010-2011 Canterbury earthquake sequence presented a unique opportunity to investigate multi-hazard events and their impacts on lifelines in a real-time reconstruction setting. The Allen *et. al*. (2014) report summarises the outcomes of their research. This focused on understanding and quantifying the impact that the earthquake hazard had on changing flood risk and flood hazard impacts from a specific flood event.

Hart *et al*. (2015) presents the outcomes of research into “Laboratory Christchurch”, where the effects of relative sea level rise and other seismic hazard effects could be assessed on a range of coastal, fluvial and built aspects of the urban environment. This is research co-lead by Dr Deirdre Hart and Sonia Giovinazzi, with a team of local and international researchers examining the multi-hazard effects of the CES. The research catalogued changes induced by the CES as they relate to coastal systems, including immediate and cascading effects on coastal environments. Effects described include changes in relative sea levels and groundwater depths; alteration of coastal embayment depths, shorelines and ecosystems extents; sediment and pollution pulses; damage to natural and engineered lifelines networks; and the migration of flooding, tsunami and chronic sea level rise hazard zones. This illustrated the interconnections between multiple coastal and river resources and hazards as a starting point to planning for greater urban resilience on seismically-active coasts worldwide.

This work drew on other post-earthquake literature and studies into the effects of sea level rise and the impacts of the CES on flooding and other hazards.

The study concluded that, within Christchurch, the cascading effects of CES induced changes in relative sea levels and other physical and built environment attributes has demonstrated the interlinked nature of many Christchurch resources and hazards as an example of a city on a recent, low-lying coastal plain in a tectonically active area being prone to multiple hazards. The research considered that the traditional approaches to urban hazard assessment where hazards are assessed individually then combined into a spatially layered system are too simplistic. It was considered that multiple hazards need to be examined in series via their linked physical and built environment attributes and cascading effects.

Further work on multi-hazards has been undertaken as part of the Heathcote River Floodplain Management Plan Project (LDRP 110). This was undertaken by the University of Canterbury under contract to Jacobs and is reported in Hart and Hawke (2016). The scope of the report was to focus on a one-way analysis of the potential effects of multi-hazards on Fluvial and Pluvial flooding hazard within the Heathcote Catchment only, as opposed to a more complex multi-way analysis of interactions between all hazards. This involved the identification of the current understanding of the following potential hazards: tsunami, coastal erosion, coastal inundation, groundwater changes, earthquakes and slope instabilitys. The knowledge of the risk, frequency and extent of impacts of each hazard were gathered and used to produce a series of maps for each hazard and the hazards co-located in hydrological catchment areas. The report then considered how any non-flooding related hazard has the potential to influence the amount of flooding across any part of the Heathcote catchment. A matrix was developed to classify the hazard intensity for the range of hazards to start to allow a comparison of the relative impacts of hazards. Hazard interactions were identified within a matrix focusing on the chance of changing the occurrence of flooding hazards. Within each sub catchment the likely hazard intensity for each hazard was also identified to allow consideration of which areas spatially were subject to a greater range of hazards. This study did identify some gas in the data available and knowledge of specific hazards. In general the gaps were not being further progressed within the LDRP110 project.

The LDRP110 project has not to date used the multi-hazard information gathered within its assessment of potential future flood hazard mitigation options. The intent is that this will be a factor within the decision making framework for that project. Hence there is not yet a practical example of the use of multi-hazards information within LDRP projects to influence the choice of flood hazard management. The LDRP110 multi-hazard information therefore sets a baseline for this project to further develop from.

3.3 Multi-hazard References

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4. Fluvial and Pluvial Flood Hazards

4.1 Overview of Christchurch Flood Processes

This overview investigates the relationship between synoptic weather and flooding in coastal Christchurch covered by the study area. Within this area, the flooding mechanisms have been identified as follows:

- Pluvial flooding associated with rainfall over Christchurch and the immediate vicinity. Studies show that much of Christchurch's short duration convective rainfall occurs as a result of low pressure and associated cold fronts moving across the region. However, longer duration (12 to 72-hour) advective rainfall events tend to occur when low pressure is centred to the east of the South Island, bringing a moist east to south-easterly airflow over the region (Macara, 2014)
- Fluvial flooding of water courses, including the Heathcote and Avon Rivers; and
- Storm surge, where sea levels are elevated by low atmospheric pressure (barometric lift) and storm onshore winds (wind stress).

While the above flooding mechanisms can and do cause flooding on their own, when they occur concurrently or in close succession, the combined effect can exacerbate the flooding hazard considerably (Wahl et al., 2015). Although there is information on actual Christchurch flood levels within the city catchments, the coincidence of the above flooding mechanisms and the relationship with synoptic weather is poorly understood and warrants further analysis, particularly as future changes in synoptic weather patterns have the potential to change spatio-temporal flooding risk.

4.1.1 Christchurch Weather and Rainfall

Canterbury weather is often changeable, with synoptic-scale weather phenomena such as anticyclones, low pressure systems and zonal westerly airflows regularly moving across the region, along with the occasional passage of ex-tropical cyclones. Within these weather patterns there are three main low pressure systems which bring rain to the Canterbury region:

- Tasman Sea lows: Low pressure systems originating from the east coast of Australia and migrating eastwards over New Zealand;
- Southern Ocean lows: Low pressure systems originating from the Southern Ocean and migrating north-eastwards over New Zealand; and
- Ex-tropical cyclones: Low pressure systems originating from the tropics and migrating south-south-eastwards over New Zealand.

The prevailing wind in Christchurch is the north-easterly, the local sea breeze which dominates the warmer months when synoptic-scale pressure gradients (and therefore synoptic-scale winds) are weak. The next most common wind direction in Christchurch is the south-westerly, which occurs following a cold front and is often connected with cold temperatures and convective (high intensity, short duration) showers.

There is a strong east-west rainfall gradient in Canterbury, with heaviest rainfall recorded in the west, closest to the Southern Alps. This rainfall generally occurs in the west to north-westerly airflow ahead of a front associated with Tasman Sea and/or Southern Ocean lows. However, further east, high intensity, low duration rainfall most commonly occurs in association with fronts moving across the region, particularly when the flow is south-westerly. Longer duration rainfall (12 to 72-hour duration) in eastern Canterbury tends to be associated with a low-pressure system centred to the east of the South Island feeding in moist east to south-easterly winds (Macara, 2014). Much of Canterbury, including Christchurch, sees its highest rainfall occurring during late autumn through winter (**Figure 4-1**; Macara, 2014). **Figure 4-2** shows ten Christchurch rainfall events which have impacted Christchurch since 1978. A mixture of long-duration/low-intensity and short-duration/high-intensity rainfall events are apparent, though events with the highest total rainfall tend to be longer duration, low intensity events.

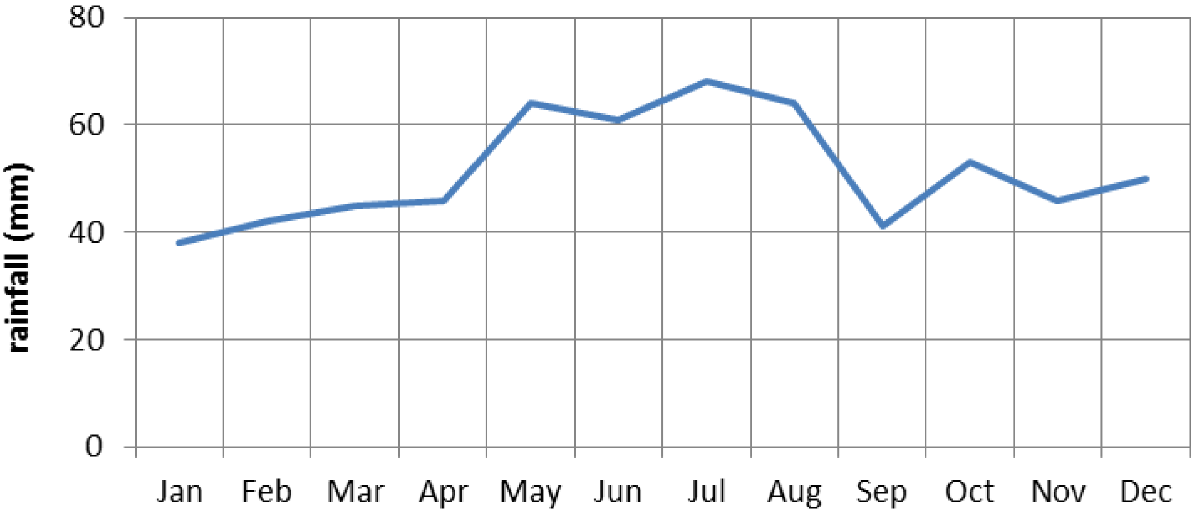

Figure 4-1 Christchurch Airport monthly rainfall normal (Data source: Macara 2014).

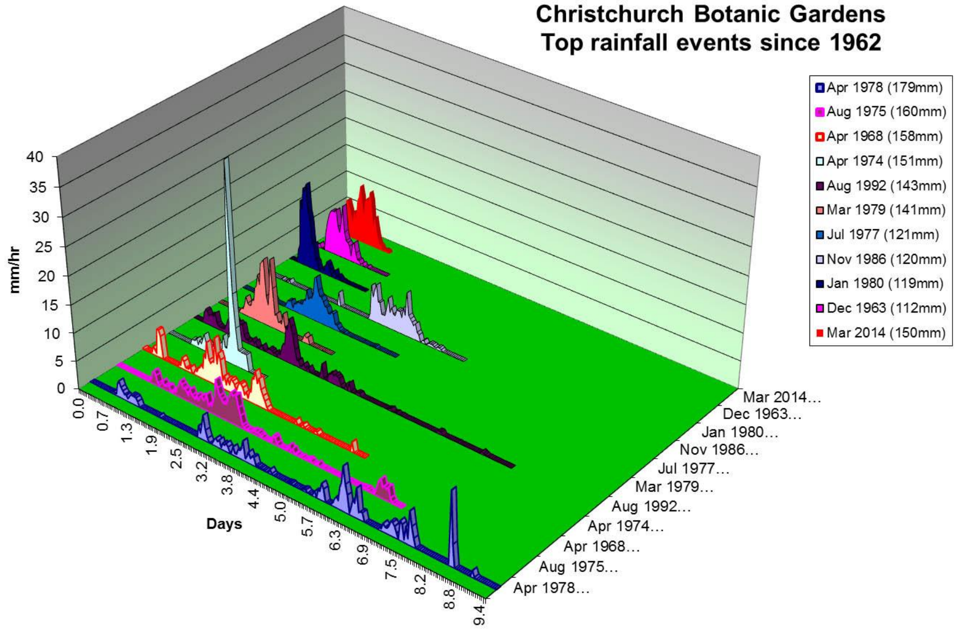

Figure 4-2 Top 10 Christchurch rainfall events, 1962 to 2017 , Christchurch Botanic Gardens automatic weather station (Graph courtesy of G Harrington, CCC 2017).

In their review of the frequency of high intensity rainfalls in Christchurch, Griffiths *et al.* (2009) provided an updated assessment of rainfall depth-duration-return period relations across the city. They found no evidence of trend, periodicity, persistence or shifts or any relationship between Christchurch rainfall factors and large-scale atmospheric phenomena such as the El Niño Southern Oscillation (ENSO), the Interdecadal Pacific Oscillation (IPO) or with climate change. From this study came the recommendation to use design rainfall events based on Extreme Value Type 1 (EV1) distributions. However, it was noted that the use of the mean annual rainfall spatial pattern works best for rainfall events of longer duration (24 hour or longer). In addition, the period 1990-2007 coincided with a relatively quiet rainfall period, with few storm events, and so rainfall depths from the Griffiths *et al.* (2009) study are around 25% lower than in the first high intensity rainfall study in 1992 (Pearson 1992, cited in Griffiths *et al.* 2009).

This study did not provide any indication of the relationship between storm duration or probability and flooding in Christchurch, nor was there any evidence of specific relationships between synoptic weather situations and rainfall events. This is important as an understanding of the relationship between synoptic weather events and rainfall distributions is a crucial step for understanding the coincidence between pluvial, fluvial and coastal flooding in Christchurch. In addition, changing weather patterns predicted over the next 100 years can be expected to have an impact on rainfall patterns in Christchurch and so a better understanding of the historic relationship between synoptic weather, rainfall and flooding can lead to an improvement in future flooding projections.

The temporal relationship between the meteorological conditions which have the ability to cause fluvial flooding in the Waimakariri River catchment, pluvial flooding over Christchurch, and coastal storm surge is currently unestablished in the literature. Increased knowledge in this area will assist with understanding the potential coincidence of these events and where coincidence would increase flooding risk, especially in coastal areas like Brooklands Lagoon. Council holds historical water level data in this area of Christchurch, which is suggested to be analysed to identify possible relationships as part of the gap filling process.

Additional fluvial and pluvial flooding information is included in **Appendix C**.

4.2 Christchurch Flood Data and Modelling

4.2.1 Existing Data and Mapping

Flood modelling and mapping across the study areas has been undertaken over a number of years and by a number of organisations. This has applied numerous methodologies, probability events, durations, development scenarios, climate change predictions etc. depending on the purpose. For the purpose of this initial review, therefore, the following flood data as adopted in the District Plan has been used in preference to collating data from multiple studies:

- Flood Management Area (FMA): Flood Management Areas are defined by the 1 in 200 year ARI plus climate change, plus a 250 mm freeboard allowance. Floor levels must be 0.4 m above these 1 in 200 year flood or tide levels, which includes 250 mm freeboard and 150 mm minimum foundation height.
- High Flood Hazard Management Areas (HFHMA). Defined as areas where, in a 1 in 500 year ARI event, flood water is deeper than 1m or the product of velocity and depth is greater than 1.

As mapped in Map A1 (**Appendix A**), these layers provide a consistent indication of known flood risk across the study areas. Section 4.2.2 below reviews the anticipated City Wide Model which will provide consistent hydraulic modelling across the study areas.

Although no city-wide analysis of the predicted consequences of flooding has been undertaken[1], Council is currently developing such an understanding for the Long Term Plan. This will include an analysis of buildings at risk of flooding across the city as measured by the following metrics:

- Overfloor flooding: water level within 100mm of floor level.
- Underfloor flooding: building footprint touched by flood extent.
- Section flooding: sections which intersect with flood extent.

Council has also recently developed a tool[2] which calculates and maps the economic damage resulting from flooding which utilises city wide flood mapping. Therefore, the current gaps in the consistent and comprehensive understanding of flood risk across the study areas are anticipated to be filled by Council within the coming months.

[1] Studies on flood consequences have been undertaken for specific events (e.g. Mayoral Task Force investigation into March 2014 flooding) and specific catchments (e.g. LDRP studies in Heathcote, Avon, Styx)
[2] Jacobs (2016) Stormwater Infrastructure Economic Tool: Case Studies Report. 19 October 2016

4.2.2 City Wide Model

GHD and AECOM are building detailed models of the Avon and Heathcote stormwater catchments, and extending the detailed modelling into new areas including Parklands, the Estuary environs and Sumner. Work is in progress and the assessment is based on the report Citywide Flood Modelling (LDRP044) Model Schematisation – Avon/Estuary, Heathcote and Sumner – Rev2 (draft), which is dated January 2017.

Models of the Halswell catchment and the Styx catchment are also being developed and are expected to have a similar level of detail.

The approach to hydrological modelling is not yet commonly used in New Zealand, and has not been critically examined by this review. The reporting of the method used indicates it is flexible enough for the likely effects of multi-hazard combinations on the hydrology to be modelled.

The report does not discuss running the model.

4.2.3 Model Capacity and Limitations

The model is capable of examining most of the multi-hazard combinations proposed in subsequent sections, though it will need modifications that range from minor to significant. These capabilities are presented in Table 4-1.

The multi-hazard combinations that are least suitable to examination with this model are those that require an understanding of either the action of wind on wide floodplains or an understanding of sediment generation within the catchment or sedimentation in the pipe and channel network.

Multi-hazard combinations that require the examination of rapid or slow changes to the terrain, changes to the relationship between terrain level and sea level, changes in groundwater levels and changes to the hydrology can be examined by modifying the current model.

Groundwater levels and their effect on the stormwater network are coarsely modelled due to a lack of detailed data. This will limit the ability of the model to be used to provide a detailed understanding of multi-hazards that result in changes to groundwater. The lack of detail relates to the spatial and temporal data.

Pre and post Canterbury Earthquake Sequence scenarios are discussed in the report. Differences are mostly on the 2D component of the model, i.e. the floodplain. Some changes are made to the open channel network where data are available or a reasonable adjustment can be made. Changes to the pipe network are limited to known post-quake works.

Table 4-1 City Wide Model Capabilities to handle multi hazard process parameters

Hazard	Physical Process	Can CWM represent this?	Comments	Gap
Earthquake	Vertical land movement	Yes		
	Liquefaction leading to channel section change	Yes		
	Broken drainage network	Yes		
Increased groundwater levels	Higher water table causing increased seepage into the stormwater network	Yes		
	Higher water table causing changes to the catchment hydrology	Not explicitly	Greater saturation and lower infiltration currently included in hydrological losses and not spatially distributed across the model	Study to link raised GW levels to modified infiltration values. Should be undertaken Stage 2.
Storm Surge	Levels in the sea and in the estuary are higher than they would otherwise be, due to lower atmospheric pressure	Yes		
	Levels in the sea and in the estuary are higher than they would otherwise be, due to wind fetch	Yes	While the software is capable of modelling this, the model is not designed for this kind of work. The effect is likely to be relatively minor. and would need a defined wind event.	
Extreme Waves	Inflows from the coast, and increased water levels	Yes		
	Erosion on the coast	Yes	Would require the implementation of a time-varying bathymetry for event-based analysis	Study to identify likely erosion scenarios
Extreme Wind	Debris generation that blocks culverts, bridges, inlets and sumps	Yes	Would require changes to the Q-H or Q-dH relationships used to describe the performance of each of the components.	Study to identify changes to Q-H or Q-dH relationships
	Generation of loess	Not explicitly	Can be modelled as a change to pipe or channel shape (silt in the invert) or as a change to Manning roughness	
	Wind shear redistributes ponded water volumes	Yes	While the software is capable of modelling this, the model is not designed for this kind of work. The effect is likely to be relatively minor.	
Sea Level Rise	Increase in downstream water levels	Yes	Already allowed for in model scenarios.	Study to determine which other scenarios to model - if any.

Hazard	Physical Process	Can CWM represent this?	Comments	Gap
	Increase in groundwater level near sea causing increased infiltration to stormwater system	Yes		
	Increase in groundwater level near sea causing decreased losses to rainfall	Yes	Changes to parameterisation used to create hydrographs in hydrological model	
Storm Intensity & Frequency	Increase in rainfall volumes and peak intensities	Yes	Already allowed for in model scenarios.	
	Change in design storm shape and profile	Yes		Study to update storm shapes and profiles
Increased groundwater levels	Already covered in rows 5 and 6 above, and also discussed in rows 15, 16 and 17			
Permanent shoreline erosion	Reduced ground levels along coast	Yes	Update bathymetry	Study to identify likely erosion scenarios
	Shortened pipelines at coast	Yes	Update pipe networks	Study to identify likely erosion scenarios and methods for continuing pipe discharge designs for the eroded coastline
	Reduced subcatchment sizes along coast	Yes	Update subcatchment areas and parameter values	
Tsunami	Large inflows and outflows, and associated rapid rises and falls in downstream water level	Yes	While the software is capable of modelling this, the model is not designed for this kind of work.	Study to determine whether the model can simulate a tsunami without being unstable. Study to identify the characteristics of a tsunami
	Erosion at estuary mouth and across dunes	Yes	Add a time-varying bathymetry	Study to determine the likely erosion effects of the design tsunami
Vertical Land Displacement	Spatially constant	Yes	Equivalent to a change in sea level	
	Spatially variable, or differential settlement causing changes to pipe and channel configuration	Yes	Update bathymetry	
			Update sub-catchment boundaries, parameter values, and connectivity	
			Update pipe and channel inverts, and channel cross sections	
Liquefaction	Changes to landform	Yes	see "Spatially variable, or differential settlement causing changes to pipe and channel configuration" above	

Hazard	Physical Process	Can CWM represent this?	Comments	Gap
Hill slope stability	Damage to pipe networks	Yes	Update or delete pipe networks	
	Changes to open channel network	Yes		
	Changes to subcatchments	Yes		
	Changes to sediment loads	Not explicitly		
Regional Flood	Inundation from upstream of city	Yes	Add inflow hydrographs	Study to identify breach scenarios
	Erosion and deposit of sediment	Yes	Update bathymetry, or apply time-varying bathymetry.	Study to identify breach scenarios and the effect on the bathymetry

4.3 Influence of Long-Term Climate Change

4.3.1 Sea Level Rise

Although the sea around New Zealand has so far risen in line with the global average (1.7mm/yr), it may rise faster in the future[3]. The most appropriate sea level rise projections to use are those from the most recent IPCC fifth assessment report (IPCC 2014) Representative Concentration Pathway (RCP) 8.5 scenario, as used in the T&T (2015) coastal hazard assessment for Christchurch. This RCP scenario is for temperature rise from a continuation of status quo greenhouse gas emissions. The 2008 National Guidance Note on Coastal Hazards (MfE, 2008) recommends that beyond 2100, a further rise of 0.01m should be considered. Based on the IPCC Fifth Assessment Report, the Parliamentary Commissioner for the Environment (2015) suggests that New Zealand should plan for a rise of 30 cm between 2015 and 2065 with a +1m rise by 2100. Sea level rise will exacerbate the existing coastal hazards of flooding, erosion and groundwater that rises too high or becomes saline. The Ministry for Environment are currently working on a revised edition of Guidance for Local Government on Coastal Hazards and Climate Change to update the recommended projections from the 2008 Guidance Note (MfE 2008) as a result of the more IPCC projections. The revised Guidance Note is due to be released during 2017.

4.3.2 Rainfall Projections

The latest IPCC report states that “precipitation projections are highly variable by region and time and between models”, both internationally and for New Zealand (Ministry for the Environment 2016). Indications are that there will be lower annual average rainfall in eastern Canterbury but that it will be wetter in the western part of the province, over the Southern Alps (Mullan *et al* 2008; Hollis 2016). This is likely to impact on the Waimakariri River catchment, with greater rainfall in the headwaters leading to increased flows and associated regional flooding.

The most common projected precipitation pattern indicates overall decreasing precipitation for coastal North Canterbury (Ministry for the Environment 2016). However, larger changes are seen at the seasonal scale, especially under the highest emissions scenarios and for the longer assessment period (to 2090). During summer, it is *likely* that there will be increases in precipitation by 2090, especially at higher greenhouse gas concentrations, at Christchurch as well as inland Canterbury. Conversely, it is *likely* (i.e. 66-100%) that there will be decreased precipitation during winter. In general, the spring season is like winter and autumn is transitional between summer and winter (Ministry for the Environment 2016). These seasonal changes in precipitation are consistent with a slight increase in convective (short duration, high intensity) precipitation. However, model guidance is inconclusive around the east coast of the South Island and so extrapolating detailed changes in rainfall intensity, duration or occurrence is still problematic (Ministry for the Environment 2016).

In the Southern Alps, a slight increase in precipitation was predicted in the IPCC 4th Assessment during summer and autumn (+1 & +2% respectively) but +8 & +6% increase in precipitation during winter and spring (Mullan *et al.*, 2008). This increase in winter precipitation was also noted in the latest IPCC report (Ministry for the Environment 2016) and is consistent with future projections of increasing zonal (westerly) flows mentioned in Section 10.3.3. However, as with Christchurch, the general uncertainty in projected rainfall changes remains large (Hollis 2016; Ministry for the Environment 2016).

4.3.3 Future Storm Projections

As discussed above, there are three main low pressure systems which bring rain to the Canterbury region. Studies have shown that the frequency of mid and high latitude low pressure systems have decreased over the Southern Hemisphere in the latter part of the twentieth century (e.g. Fyfe, 2003; Simmonds and Keay, 2000), especially in mid latitudes, with a slight increase in high latitudes (Lim and Simmonds 2009). This trend is apparent over New Zealand, and is projected to continue. Tasman Sea Lows, which usually occur in the winter season and are associated with occurrences of extreme rainfall, winds and waves in New Zealand, are

[3] Parliamentary Commissioner for the Environment (2015) Preparing New Zealand for rising seas: Certainty and Uncertainty. November 2015.

predicted to reduce in frequency by 30 per cent (mainly in winter) between the late 20th century and the late 21st century (Dowdy *et al*., 2013).

There are indications that Southern Ocean low pressure systems will also decrease in frequency across Canterbury through the 21st century. However, **Figure 4-3** (which shows potential changes in the Southern Hemisphere storm track under a high emission scenario) illustrates the low confidence in this projection, with poor model agreement in this region (IPCC 2012). While there is low confidence in the detailed geographical projections of extratropical cyclone activity, there is medium confidence in a projected poleward shift of extratropical storm tracks (IPCC 2012).

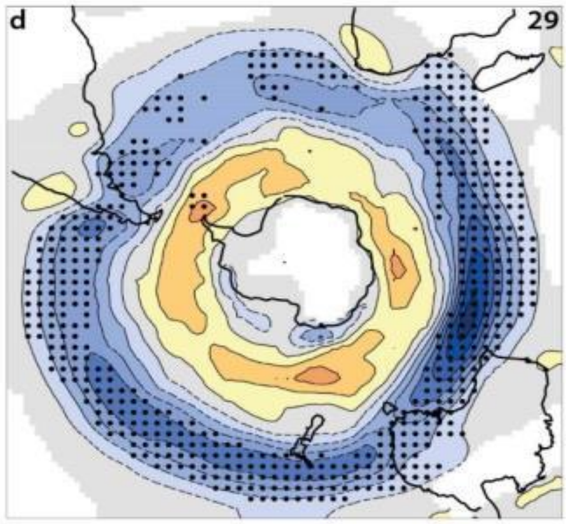

Figure 4-3 Change in winter Southern Hemisphere storm track between 1986-2005 and 2081-2100 under RCP8.5, from a 29-member CMIP5 multi-model ensemble Blue shading indicates a decrease, and yellow-orange shading an increase in the number of storm 'centres'. Stippling is added where 90 per cent of the models agree on the sign of the change (from Ministry for the Environment 2016).

The final weather type that brings rain to Canterbury is the ex-tropical cyclone. In global terms, the IPCC has reported that it is likely that the number of tropical cyclones will either decrease or remain the same over the next century. However, it is also likely that tropical cyclones will be stronger – stronger winds and greater rainfall intensities. But "there is low confidence in region specific projections" as current climate models do not have sufficient resolution to reliably simulate tropical cyclones (Ministry for the Environment 2016).

4.3.4 Christchurch City Modelling Scenarios

The Waterways, Wetland and Drainage Guide (Chapter 21, amended December 2011) states that a 16% increase in rainfall by 2100 should be adopted for Christchurch as the basic storm rainfall design standard.

Figure 4-4 illustrates how temperature is projected to rise in Canterbury in the RCP scenarios of RCP 2.6 (stringent mitigation pathway), 4.5 (stabilisation pathway) and 8.5 (business-as-usual). Using consistently projected changes in both rainfall and sea level rise will allow flood impacts through time to be better defined, where the times are related to the IPCC climate projections for use in economic analysis and implementation programmes.

The LDRP110 project has defined decadal increases in sea level and rainfall for the three different RCP scenarios. Rainfall increases are specific to different probability events. The methodology was developed for the Heathcote catchment but is applicable across Christchurch. It is recommended that modelling in this multi-hazards study uses this same approach of estimating the combined effects of climate change on extreme rainfall events and sea level rise.

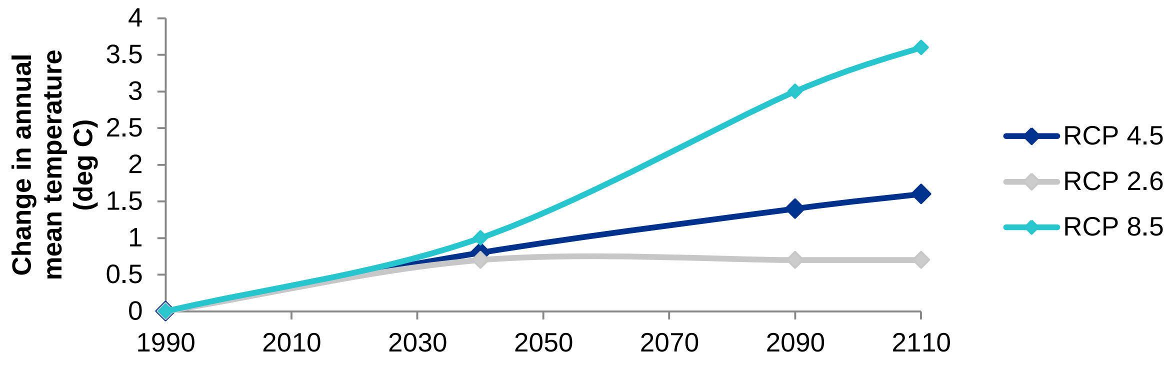

Figure 4-4 Graph of projected temperature changes in Canterbury under all RCP event mean values

4.4 Key Gaps in Flood Knowledge and Modelling

A key gap identified is the coincidence between different types of synoptic weather and flooding in Christchurch. To date there has been little research which shows the links between fluvial flooding and associated weather conditions in the study area.

While the relationship between rainfall and synoptic weather patterns affecting the region is well established, there is no data analysis on the relationship between meteorological events which produce fluvial and/or pluvial flooding and coastal flooding (storm surge) in Canterbury, or how they might coincide.

Gaps: Ongoing uncertainties in projected rainfall characteristics under climate change; uncertainties in future projections of ex-tropical cyclone activity and associated possible underprediction of rainfall from these events; Uncertainties in future projections of extra-tropical cyclone activity.

Table 4-3 Gaps relevant to assessment of future extreme rainfall events

Gap Description	Benefit if Addressed / Risk if not Addressed	Indicative Budget Estimate and Timescale Required
Relationship between different types of storms and flooding While Griffiths *et al*. (2009) have provided an assessment of Christchurch rainfall, there is no data analysis on the relationship between meteorological events which produce fluvial and/or pluvial flooding and coastal flooding (storm surge) in Canterbury, or how they might coincide. Undertaking a storm weather analysis project should investigate: • the relationship between synoptic weather events and past Christchurch coastal / fluvial / pluvial flooding (Kidson synoptic weather analysis of past flooding events); o Waimakariri and Styx flood coincidence o Waimakariri and Avon/Heathcote flood coincidence o Coastal flood coincidence o Pluvial flood coincidence • the relationship between synoptic weather, hail, snow and wind events and flooding (Kidson synoptic weather analysis); ▪ Hail / snow melt correlation and relationship with antecedent conditions; • Coastal storm correlation and features (including Bathymetric lift, wind/wave setup, coastal inundation, high tide);	Benefit: A better understanding of the impact of different types of synoptic weather situations on flood risk in the study area. Risk: Flood risk may be underestimated and future freeboard allowances may not cater for increased wind or storms	Budget Estimate: High Requirement: Within project

Gap Description	Benefit if Addressed / Risk if not Addressed	Indicative Budget Estimate and Timescale Required
• Groundwater elevation / correlation		
Future changes in rainfall Ongoing uncertainties in projected rainfall characteristics under climate change	Benefit: Increased understanding.	Budget Estimate: Medium Requirement: Outside of project
Future changes in ex-tropical cyclone activity Uncertainties in future projections of ex-tropical cyclone activity and associated possible underprediction of rainfall from these events	Benefit: With ex-tropical cyclones significant rain-making events, this is a source of considerable uncertainty in future rainfall and therefore flooding predictions. An improvement in these uncertainties would result in an improvement in future flooding risk estimations for Christchurch. Risk: underprediction of rainfall brings the risk of underestimation of flood risk.	Budget Estimate: Medium Requirement: Outside of project
Uncertainty in extra-tropical storm projections Uncertainties in future projections of extra-tropical cyclone activity.	Benefit: This can build on results from the storm weather analysis gap project where, if a certain type of storm event is associated with a certain type of flooding event (or a certain location), then knowledge of future storm projections can improve future flooding projections with impacts on possible flooding solutions. Risk: Flood risk may be under or overestimated.	Budget Estimate: Medium Requirement: Outside of project

4.5 Fluvial and Pluvial Flood Hazard References

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PART 1: NON-FLOOD HAZARD EVENTS GAP ANALYSIS

5. EXTREME WEATHER EVENTS

5.1 Overview of Event Physical Processes

5.1.1 Coastal Storm

Coastal storm events involve the combination of elevated sea levels from storm surge and elevated wave run-up from extreme wave events. There are a number of meteorological and astronomical phenomena which are involved in the development of a combined extreme 'storm-tide' and 'wave event'. These processes can combine in a number of ways to inundate low-lying coastal margins or cause coastal erosion.

Storm tide is defined as the sea level peak around high tide during a storm event, resulting from the combination of the following:

Storm tide = astronomical high tide + MSLA + storm surge

Where MSLA is the Mean Sea Level Anomaly which is the non-tidal variation in sea level at scales from monthly to decades due to climate variability (e.g. ENSO & IPO) and season effects, and storm surge is the rise in sea level due to storm meteorological effects.

There are two components to storm surge:

1) Barometric lift, being the rise in sea level when low-atmospheric pressure relaxes the pressure on the ocean surface causing the sea-level to rise. The standard relationship being expressed as 1 cm of sea level rise for every mb of pressure below 1013mb.
2) Wind stress on the ocean surface pushing water down-wind or to the left of alongshore wind (for southern hemisphere) from a persistent wind field to pile up against any adjacent coast. Hence for the Canterbury coast, wind stress occurs for SE onshore winds and SW alongshore winds (Stephens *et al*., 2015). The magnitude of wind stress is depend on the wind speed, with gusty winds producing larger stresses than steady winds of the same average speed.

In New Zealand, storm surges are unlikely to exceed 1m (Bell *et al*., 2000) and has timescales of sea-level response that coincide with synoptic weather motions - typically in the range of 1–3 days.

Where there are good long-term sea levels records, probabilistic estimates of extreme storm-tide levels are usually predicted by fitting a statistical extreme-value model (e.g. generalised extreme value (GEV) or Generalised Pareto Distribution (GPD) model) to a subset of independent maxima from an existing sea level record (Coles, 2001). In this way the very largest events in the record are extrapolated to estimate even larger events that might occur but have not been recorded over the usually limited duration of sea-level recordings. Where sea level records are shorter (e.g. do not cover a number of decades) other methods are used such as Monte Carlo stimulation techniques involving randomly combining the individual components of the storm tide to produce a large data set (e.g. 1000s of years) of stimulated annual sea level maxima (Goring *et al* 2010).

Wind-generated waves also raise the effective sea level at the coastline by two processes.

1) Wave setup, being the temporary increase in mean still water level at the coast that results from the release of wave energy in the surf zone as waves break. Wave setup is an integral component of the total water level that potentially could cause direct or near-continuous inundation of "green water" onto coastal land.
2) Wave run-up is the maximum vertical extent of wave "up-rush" on a beach or structure above the instantaneous still-water or storm-tide level (e.g. water level that would occur without waves), and thus constitutes only a short-term fluctuation in water level relative to wave setup, tidal and storm-surge time scales. However, the combined storm-tide plus wave run-up level is relevant to beach erosion, wave impact on seawalls and sand dunes, and can result in wave overtopping of both of these primary coastal defence systems .

When offshore waves are large, wave setup and run-up can raise the water level at the beach substantially, especially on steeper beach slopes or steep-face structures such as rock revetments or seawalls. For practical purposes, wave set-up and run-up levels are typically calculated using empirical formulae. For sand beaches there are a wide range of formulae available, most of which take account of the significant wave height and period outside the breaker zone, and average beach slope.

A typical approach to deriving the necessary nearshore extreme wave conditions involves using a hindcast time series of offshore wave data over a 20-40 year period calibrated against any available offshore wave buoy or satellite data, then using coastal area wave models to simulate the propagation of the offshore waves to the coastline (e.g. SWAN model) (Ramsay et al., 2012). Once a time series of wave conditions has been derived at each location of interest, a statistical extreme-value model is used to derive extreme statistics.

For New Zealand, the NIWA Wave and Storm Surge Predict models (WSAP) produce 45-year (1958-2002) and 30 year (1970-2000) hindcast records around the entire country. For Canterbury the Banks Peninsula wave buoy provides a wave record for the Canterbury Region since 1994.

Once extreme statistics have been derived for both storm tide and wave conditions at each location, joint probability techniques (Hawkes, 2002) can then be used to assess the interdependence between extreme waves and water levels. Correlations between high waves and high water levels can occur for two main reasons Ramsay *et al*., 2012):

1) Meteorological. However, since the astronomical (tide) component of storm tide is usually larger than the surge component, any such correlation may be modest.
2) Depth-limited waves, where wave heights are dependent on the storm tide level. In this case the degree of dependency will depend on the depth of water where nearshore wave conditions were derived.

Although the various components that combine to result in extreme storm tide are typically correlated in some way, very rarely does an extreme high tide level coincide with a high storm surge and high wave conditions (Ramsay & Stephens, 2006). Simply assuming that an extreme sea level will always occur at the same time as extreme wave conditions will tend to overestimate inundation risk.

5.1.2 Snow Events

Snow is precipitation composed of ice crystals which are usually clustered together into snowflakes. If the air falls below around -10°C, ice crystals will start to grow more rapidly than water droplets. As these ice crystals move around in the air they collide and stick together. The type of solid precipitation is indicative of the strength of vertical motion within a cloud, where snow is formed under low vertical motion conditions, but greater vertical motion results in more violent collisions between the ice particles and the production of graupel or hail (these are discussed in Section 2.1.3).

While cold polar air over the region alone may bring snow to low levels, this situation does not tend to bring large amounts of snow as the amount of water that air can hold is dependent on temperature i.e. cold air can hold less moisture than warm and so has less water available to precipitate out. Heaviest snow events in Canterbury tend to occur as a result of the interaction of very cold polar air with warmer, moist air from the sub-tropics, where this warmer air brings an injection of moisture which condenses into ice crystals as it rises above freezing level. Conversely, the cold dense air at the surface means that, when the snow falls, it is less likely to melt before it reaches the surface. Snow in Canterbury occurs primarily when a low pressure system is located to the south-east or east of the South Island, such as illustrated in Figure 5-1. In this example, a low pressure system tracked south-eastwards across the Tasman Sea, bringing relatively warm, moist air with it (Figure 5-1a). After crossing the country, it drew very cold air from the Southern Ocean northwards over Canterbury (Figure 5-1b), resulting in widespread snow across Christchurch and the Canterbury region (Hendrikx 2007) Deeper low centres, associated with stronger convection, lead to increased snow risk to low levels in Canterbury (Hendrikx et al. 2012; Macara 2014).

The annual average number of snow days at Christchurch Airport is given as three (Macara 2014), where this number is derived from direct snow observations.

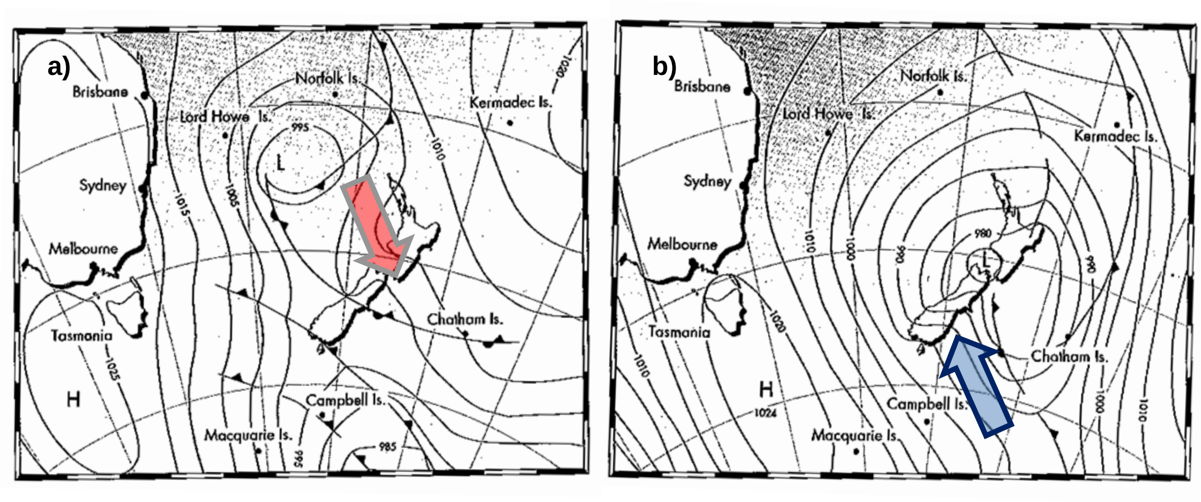

Figure 5-1 Synoptic weather maps from the 27–29 August 1992 snow storm for a) 26th August 1992 and b) 27th August 1992. The red arrow shows warm moist air and the blue arrow indicates cold air (Maps sourced from http://educo.vln.school.nz/mod/book/tool/print/index.php?id=5453)

5.1.3 Thunderstorm & Hail Events

Thunderstorms are uncommon in Christchurch, but are most frequently observed around mid-afternoon during warmer months indicating that a major trigger mechanism for the thunderstorm is surface heating (Revell, 1984; Hawke 2017). They tend to occur in unstable south-westerly airflows following the passage of a front over the region (**Figure 5-2**).).

Hail is solid precipitation produced in deep convective clouds (i.e. thunderstorms), with a diameter greater than 5mm (Punge & Kunz 2016; AMS Glossary 2017). Conditions conducive to hail formation and growth are strong vertical motion within the cloud, large supercooled liquid water contents and high cloud tops (i.e. well above the freezing level). These properties allow the hailstone to freeze and sublimate for a length of time sufficient to allow it to grow via accretion and/or by collision and aggregation (Punge & Kunz 2016). Hail has a solid structure as a result of stronger updrafts and more violent collision compare to snow. However, graupel is often mistaken for hail, where graupel is a heavily rimed snow particle, often called a snow pellet but is not associated with thunderstorms. Graupel is often indistinguishable from very small soft hail except for the size convention that hail must have a diameter greater than 5 mm.

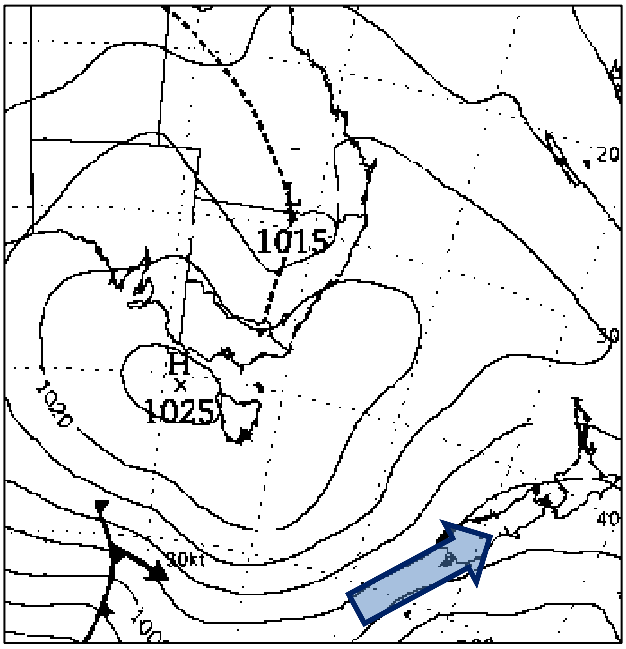

Figure 5-2 1pm 14th Dec 2009 synoptic weather map for the 14th December 2009 Canterbury thunderstorm sequence (map sources from the Bureau of Meteorology).

5.1.4 Extreme Wind

Extreme wind events can occur due to several different weather situations in Christchurch. Firstly, very strong gusty south to south-westerly winds can occur during the passage of an active cold front over the city. Because this is also a weather situation which can cause pluvial flooding, any damage or debris caused by these winds can block drains and cause or exacerbate surface flooding.

Secondly, north-westerly wind storms associated with foehn conditions can bring more sustained periods of high wind. A foehn wind – called a nor-wester in Canterbury – is a dry, warm wind that occurs to the lee of a mountain range. It can be associated with strong winds as the mountains block the low-level airflow, with stronger high-level winds drawn down to the surface over Canterbury as a result (Sturman & Tapper 1996). The nor-wester usually precedes the passage over a cold front over the region, followed by a south-westerly change and so any wind damage or debris has the potential to create or exacerbate pluvial flooding hazards associated with the frontal rain.

Thirdly, locally severe wind gusts can occur in association with thunderstorms. As thunderstorms are also associated with short duration, high intensity rainfall, any wind damage can also negatively impact drainage network capabilities. Thunderstorm hazards impact smaller areas and so some localities may be severely affected, while others remain unscathed.

The prevailing wind in Christchurch is the north-easterly, associated with the generation of the sea-breeze during warmer months. However, extreme wind events in Christchurch tend to be associated with the nor-wester or with south to south-westerly airflows. Wind speeds are typically highest from October to January, and lowest from April to August (Macara 2014).

5.2 Christchurch Data and Modelling

5.2.1 Coastal Storms

For the prediction of extreme storm tide levels within the central Canterbury area, including Christchurch, records from the Lyttelton tide gauge has been used (Stephens *et al.,* 2015). Over 100 years of record is available from this gauge, which make it suitable for both GEV (Generalised Extreme Value) and MCJP (Monte Carlo Joint Probability) statistical analysis of extreme storm tides (Stephens *et al.,* 2015). The results from this analysis are shown in **Table 5-1**.

Table 5-1 Extreme storm tide frequency-magnitude distributions at Lyttelton (from Stephens *et al* 2015, Table 6.4)

Method	AEP	0.02	0.01	0.005
	ARI	**50yr**	**100yr**	**200yr**
GEV maximum likelihood		1.66	1.68	1.70
GEV lower 95% confidence interval		1.60	1.61	1.62
GEV upper 95% confidence interval		1.76	1.79	1.82
MCJP maximum likelihood		1.69	1.71	1.74
Note: Elevations are relative to MSL. Add 0.165 as current MSL has been calculated over (1993-2012) to make them relative to LVD-37 datum.				

It is noted that the storm tide levels (relative to LVD-37) given in Tonkin & Taylor (2015) for the 1% and 2% AEP events, fall in the range of the above values from Stephens et al (2015). The Tonkin & Taylor (2015) levels are given as being sourced from Goring et al (2009) based on the Lyttelton tide gauge data (1998-2009) using an Empirical Simulation Technique.

Tonkin & Taylor (2015) also presents 1% and 2% AEP extreme storm tides for Sumner sourced from Goring *et al* (2010) as being 0.07m lower that the corresponding probability storm tide at Lyttelton. Similar extreme storm tide levels for Sumner were obtained by Robinson (2015) for a shorter record from the Sumner Head sea level recorder. Stephens *et al* (2015) noted that large waves affected the quality of the sea level records at the Sumner gauge for a period of time.

Stephens *et al* (2015) used the 30 year (1970-2000) WASP hindcast wave record, calibrated by the 15 years of record from the Banks Peninsula wave buoy to generate an extreme wave distribution for 29 inshore locations along the Canterbury coast. Under prediction of extreme waves by the WASP model compared to actual measured waves by the buoy was overcome by applying a scaling factor to the model results. The resulting stimulated extreme wave heights for the Christchurch locations are presented in **Table 5-2**.

Table 5-2 Stimulated extreme wave height distributions for Christchurch (from Stephens et al 2015, Table 6.5)

Location	Annual Exceedance Probability (AEP)		
	0.02	**0.01**	**0.005**
Pines Beach	3.33m	3.43m	3.51m
Waimari Beach	2.64m	2.66m	2.69m
New Brighton Beach	3.29m	3.34m	3.38m
South New Brighton	3.29m	3.34m	3.38m
Sumner	3.29m	3.34m	3.38m

Since many of the large waves affecting the Canterbury coast are generated in the southern ocean, the blocking effect of the Banks Peninsula results in the extremes at these sites being less than over open coast sites in the region.

Tonkin & Taylor (2015) also present extreme wave heights used in their wave set up calculations, but these are for deep water sites, so are not directly comparable to the above wave heights. However, it is noted that these deep water heights are sourced from Tonkin & Taylor (1998), which as noted in the peer review of the Taylor & Taylor (2015) assessment (Kenderdine *et al* 2016) should be updated. The wave set-up in the 2015 assessment that would occur with 2% and 1% AEP storm tide in association with future sea level rises is given as being in the range 1.49-1.53m for New Brighton and 1.27-1.31m for Sumner. However, no information on how this was calculated is given. As noted in Kenderdine *et al* (2016) there is also no calculations of run-up included in the 2015 assessment, which the peer review recommended be addressed in the re-assessment.

To account for the presence of some dependence between storm tides and waves, Stephens *et al* (2015) presents a joint probability analysis of storm tide and wave height using the JOIN-SEA program developed by HR Wallingford (2000). The analysis showed that the highest level of dependence occurred along the Christchurch coast in the lee of Banks Peninsula, where large storm tides and large waves trended to occur together more frequency that for other parts of the Canterbury coast. The resulting joint probability distribution for South New Brighton is shown in **Figure 5-3**.

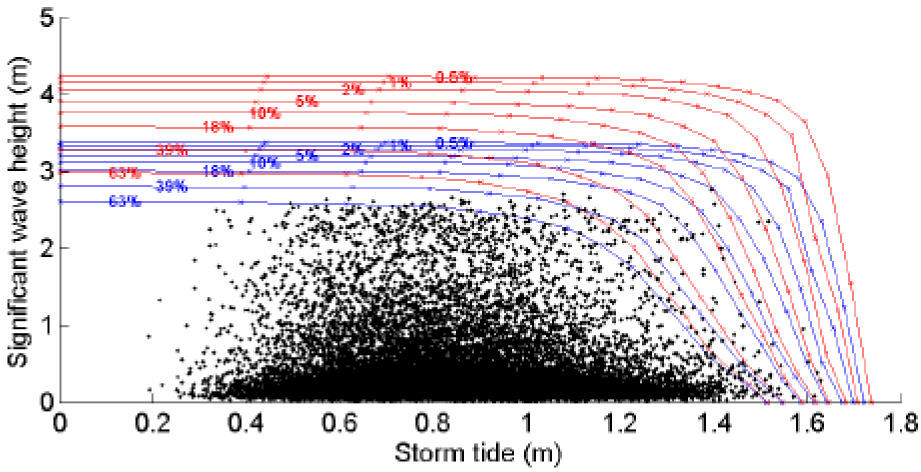

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Figure 5-3 Joint probability of storm tide and wave height at South New Brighton (from Stephens et al 2015, Figure 6.11)

The coastal calculator presented by Stephens *et al* (2015) uses formulae from Stockdon *et al* (2006) to calculate storm wave set-up and run-up, which were developed from empirical measurements on 10 natural sandy beaches in the USA and the Netherlands. Inputs into these formulae are offshore wave height and wave length, and beach slope. The resulting total water levels for the joint probability storm tide and wave heights with wave set-up and combined set-up and run-up for the Christchurch sites are presented in **Table 5-3**.

Table 5-3 Water levels for joint probability storm tide, combined with wave set-up and run-up for Christchurch sites (from Stephens *et al* 2015 coastal calculator)

Location	Annual Exceedance Probability (AEP)								
	0.02			0.01			0.005		
	ST	ST + WSU	ST + WSU + WRU	ST	ST + WSU	ST + WSU + WRU	ST	ST + WSU	ST + WSU + WRU
Pines Beach	1.42	1.87	2.47	1.50	1.93	2.50	1.53	1.99	2.65
Waimari Beach	1.48	2.12	2.87	1.50	2.16	2.96	1.58	2.22	2.98
New Brighton Beach Dunes No Dunes	 1.42 1.48	 2.22 2.04	 3.24 2.78	 1.50 1.56	 2.31 2.12	 3.34 2.87	 1.53 1.58	 2.37 2.16	 3.45 2.95
South New Brighton	1.48	2.19	3.17	1.56	2.26	3.25	1.58	2.31	3.34
Sumner	1.48	2.63	4.09	1.50	2.71	4.25	1.53	2.73	4.28
Note	All elevations given in terms of above 1993-2012 MSL, which is +0.165 m offset from LVD-37.								

It is recognised that there is a great deal of uncertainty around the results from these empirical run-up equations due to being extremely sensitive to beach slope (Stephens *et al* 2015). To overcome this uncertainty, Stephens attempted to validate the total run-up elevations against a limited number of observed debris lines from ECan beach profiles. Although the results of this validation were that the majority (87%) of all calculated run-up estimates were within ±1m of the observed run-up, it is considered that for Christchurch beaches the observed debris lines are unlikely to be a reliable indicator of storm run-up due to the high presence of dune scarps in these events In these circumstances the calculated run-up elevation is likely to be less than the theoretical possible run-up if foredune dune collapse had not occurred.

5.2.2 Snow

Hendrikx (2007) documented seven significant historical snow events affecting Canterbury along with their impacts. Events analysed were the storms of 12–14 July 1945, 16–19 November 1967, 5–6 August 1973, 27–29 August 1992, 9–13 June 1996, 17–19 June 2002 and 12 June 2006. Five of these events (1945, 1992, 1996, 2002 & 2006) saw snow in Christchurch, with maximum snow depths of 5-40 cm recorded in Christchurch. It should be noted that it is difficult to accurately compare data between events. It is also notoriously difficult to obtain accurate assessment of snow coverage for individual events based on point observations due to substantial spatial variations in snowfall and settlement as a result of wind transportation and interactions with topography and surface inhomogeneities.

While impacts such as storm damage and stock losses were outlined in this paper, there was no mention of flooding occurrences or impacts. Brenstrum (1998) noted that the August 1992 event did not lead to flooding, though there was the fear that it might. This never eventuated because the snow event was followed by a nor-west wind event which brought dry windy conditions, leading to high evaporation rates (Brenstrum 1998). However, it has been noted that there is anecdotal evidence of flooding in Henderson's Basin during this event. No other research has been found documenting the relationship between snow events and flooding hazards in Christchurch or the Canterbury region.

Within the Waimakariri catchment the estimates of the contribution of snow melt to the river flow range from 11% at the Old Highway Bridge, close to the river mouth (Cowie *et al.,* 1986), to 6% (Moore and Prowse, 1988). More recently, it has been re-assessed at 8% where meltwater was based on estimates of mean annual snow accumulation (Kerr, 2014). While snowmelt in the South Island is nowhere near as significant as in many regions of the world (Kerr, 2014), it is recognized as being able to enhance flood magnitudes when snowmelt occurs on top of rainfall events, mainly during spring and summer (Moore and Prowse, 1988). Conversely, snow can decrease the risk of flooding during winter months when precipitation falls as snow in the upper reaches of the catchment and goes into snow storage instead (Jowett and Thompson, 1977, cited in Kerr, 2014).

5.2.3 Hail

There is an average of 49 hail days reported in Christchurch each year (Macara 2014), though it is noted that "hail days" includes days in which graupel was observed. Conversely, thunderstorms, during which true hail occurs, are only recorded an average of three days each year at Christchurch Airport (Macara 2014).

There are two major sources of error in hail observations. The first is the prevalence of misclassification of graupel as hail. The second major source of observational uncertainty is the bias of observations to populated areas and within range of weather stations. While hail proxies from radar and satellite are now available, hail observation relies heavily on traditional weather observations, with associated scale issues and spatial data gaps bringing considerable uncertainty into any hail frequency evaluation (Punge & Kunz 2016). Consequently, there continues to be a low confidence in observed hail trends internationally as well as in New Zealand.

The last published assessment of hail in New Zealand was published in 1984 (Steiner, 1989), with the latest Canterbury climate publication citing average number of hail days using the same method, using hourly weather station data which record both hail and graupel as hail (Macara 2014).

Uncertainties in the reliability and/or completeness of observed hail data not only affects what we know about the current spatial and temporal variability of hail. It also adds a considerable uncertainty into any assessments of future hail projections under climate change. This means that there is only a low confidence in any future hail projections, even before modelling uncertainties are considered, (IPCC 2012). The low confidence in both current trends and future scenarios in hail occurrence is especially relevant in the New Zealand context.

5.2.4 Extreme Wind

Mullan *et al*. (2011) analysed wind speed data against Kidson weather types to understand the causes and variations of extreme winds across New Zealand. They found that large parts of New Zealand (including the Canterbury region) experienced strong daily average wind conditions primarily during trough and zonal weather situations (T, SW, W and HNW). A separate analysis of extreme wind gust and wind damage reports found that Kidson types T, SW, TSW, R and HW (in descending order of frequency of occurrence, based on interpretation of Figure 3a. in Mullan *et al.* 2011) are associated with wind gusts and damage in coastal Canterbury, with zonal (westerly) airflows producing strongest winds inland (i.e. the nor'wester). Low pressure centres associated with these extreme wind events were most often located to the east or south of the South Island (Mullan *et al.* 2011 Figures 5 & 6).

5.3 Interactions between Extreme Weather Events and Flooding

This section briefly outlines the process-response interactions and triggers associated with the co-incidence and cascading of extreme weather events with Christchurch FPF events.

5.3.1 Coastal Storms

The likelihood of co-incidence and cascade of coastal storms with FPF events are both considered to be high, but the potential exacerbation of flood magnitude and extent of co-incidence is considered to be much greater due to the high number of process-response interactions and lack of geomorphic change that could influence flooding associated with coastal storms.

Co-incidence

Due to the similar meteorological conditions potentially being responsible for causing both coastal storms and FPF events, it is considered that the likelihood of co-incidence of the two events is high. The process-response interactions of relevance to flooding of such a co-incidence could include:

- Potential direct inundation with extreme storm tide levels in the Ihutai/Avon-Heathcote Estuary and Brooklands Lagoon, and at low coastal hinterland area in Sumner.
- Extreme storm tide levels in Ihutai/Avon-Heathcote Estuary and Brooklands Lagoon producing flood backwater effects that restricts flood discharge, hence potentially result flooding in these areas and lower river channels. The current practice of determining flood heights by assessing the higher of a 1:50 year tide with a 5 year storm versus a 1:50 year storm with a 5 year tide is unlikely to capture the full range of interactions between storm tides and flooding.
- Wave run-up on the Ihutai/Avon-Heathcote Estuary and Brooklands Lagoon resulting in inundation and erosion of shoreline fringe in these areas.
- Potential dune breaches from extreme storm tide and wave run-up resulting in surface flooding on open coast fringe, particularly where there are existing gaps in the dunes (e.g. South Brighton, New Brighton), with additional water flow into the Brighton Spit stormwater network and ultimately into the Ihutai/Avon-Heathcote Estuary.
- Potential stormwater drain back-up effects at Sumner.
- Potential mouth migration/instability associated with erosion of ends of Brighton and Brooklands Spits. This is a potential issue in storms occur in quick succession, without time to recover rather than individual storm events, but also linked to climate changes in sediment supply, intense storm events and transport.

Cascades

The likelihood of a cascade from a coastal storm to a Christchurch FPF event is also considered to be high. However, the permanence and scale of the physical impacts effecting flooding (e.g. morphological change) is considered likely to be low, expect for potential mouth instability resulting from erosion of the distal end of Brighton and/or Brooklands Spit in a cluster storm cluster. To account for the potential change in mouth position the consequences on flood magnitude and extent of a cascade is considered to be moderate.

5.3.2 Snow and Hail

Co-incidence

Based on the limited number of times it has occurred; it is considered that there is a low coincidence of snow and hail in association with FPF events in Christchurch. However, no studies have been sourced to establish any linkages and processes interactions. One potential interaction is the ability for snow and hail to block gutters and drains over the short term, and so potentially result in localised surface flooding if a snow event is followed rapidly by an extreme rain event. Similarly significant snow event in Christchurch and/or the Port Hills, are typically likely to take 1-3 days to melt, so there is the potential to change antecedent soil moisture conditions, with a flow on effect in the event of a subsequent extreme rainfall event within a short time period.

Snow melt in the upper Waimakariri catchment can coincide with a significant nor-west precipitation events in spring or summer, therefore increase flood potential in the Waimakariri River, in the context of this study, this is dealt with within the regional flooding chapter.

Cascades

Based on the low frequency of extreme snow and hail events in Christchurch, the likelihood of a cascade to a Christchurch FPF event is also considered low. There is also likely to be a lack of permanence or scale of any physical impacts (e.g. morphological change) that would exacerbate flooding over a longer timeframe. Therefore except of the short-term impacts on drainage and antecedent soil moisture conditions dealt with in co-incidence, the consequences on flood magnitude and extent of a cascade is considered to be very limited.

5.3.3 Extreme Winds

Coincidence

Extreme winds can impact flooding primarily through increase in the wind stress component of storm surge, and increase in local wave heights with strong or long fetch onshore winds. The impacts of these co-incidences are listed in section 5.3.1 (Coastal storms).

In addition to coastal storm surge, strong winds and wind gusts occurring in conjunction with or in close temporal proximity to heavy rain can exacerbate flooding by wind debris blocking drainage systems. There is also the potential for wind hazards to hinder emergency response e.g. fallen trees and branches blocking roads, downed power lines and associated hazards.

Cascades

While the likelihood of a cascade from an extreme wind event to a Christchurch FPF event is considered to be moderate, there is likely to be a lack of permanence or scale of any physical impacts (e.g. morphological change) that would exacerbate flooding. Therefore it is considered that there will be no consequences on flood magnitude and extent of a cascade.

5.3.4 Summary

Based on the above discussions, the anticipated likelihood of co-incidence and cascades, and their consequences for exacerbating flooding are presented in **Table 5-4.** The rankings of High, Medium and Low used in the Table are quantitative assessments assigned by the authors to representative the relative differences in likelihood and consequence. Probabilities of occurrence or magnitude of consequence have not attempted to be qualified.

Table 5-4 Summary of Anticipated Co-incidence and Cascade impacts for Extreme Weather Events and Christchurch FPF Events

Interaction with FPF Events	Coastal Storm	Snow & Hail	Extreme Wind
Co-incidence Likelihood	**High**	**Low**	**Low** Except for coastal storms
Co-incidence Consequence for exacerbating flooding	**High**	**Moderate** Block drains Change antecedent conditions	**High** for coastal storms **Low** for other extreme wind events
Cascade Likelihood	**High**	**Low**	**Moderate**
Cascade Physical Impact Permanence	**Moderate** Estuary/River mouth migration	**Nil**	**Nil**
Cascade Consequence for exacerbating flooding	**Moderate** Estuary/River mouth migration	**Very Low** Only if very short term Cascade of events	**Nil**

5.4 Influence of Long-term Climate Change on Extreme Weather Events

5.4.1 Sea Level Rise

Long-term sea level rise will increase the effect of coastal storm events, due to them increasing the storm tide level for the same probability event. Hence, we would expect greater erosion and inundation in storm events in the further than currently occurs for similar wave heights.

5.4.2 Storm Intensity and Frequency

Coastal Storms

The possible influences of climate change on coastal storms include increase in Ex Tropical Cyclone occurrence, increased storm surge, and increased wave climate. The current state of the knowledge on these impacts is as follows:

- Tropical Cyclones: IPCC (2012) predict that in a global context, the frequency of tropical cyclone frequency will either decrease or remain the same, but that there will be a likely increase in associated wind speeds. However, this pattern may not occur in all oceanic regions. Projections indicate that tropical cyclones may move further southwards in the Southwestern Pacific as sea surface temperatures increase, is some evidence to suggest the zone in which cyclones form and decay may change by around 100 kilometres further south during this century (Australian Dept of Environment and Energy: http://www.environment.gov.au/climate-change/climate-science/impacts/qld); It is unclear how this might impact on New Zealand (Royal Society of New Zealand 2016). However, it seems likely that if there is an increase in tropical storm intensity through the 21st century, this would result in higher intensity ex-tropical cyclones affecting New Zealand and greater storm impacts.

- Storm Surge: The NIWA Wave and Storm-surge Projections (WASP) project indicates that storm surge will increase by in the order of + 0.05m by 2100 with climate change (Gorman 2016).

- Wave Heights. Gorman (2016), also reported that the outputs of the WASP were for annual wave heights to increase by a maximum of 2-3% by 2100 in southern New Zealand, with small decreases in the NE of the North Island.

Snow

Climate change is expected to alter the distribution, extent and duration of seasonal snow, as well as change the melt regime. Increasing temperatures increases snowmelt, affects runoff and infiltration which can have a direct impact on slope stability – where increased pore water pressure and decreased strength, along with and increased ratio of rain to snow, can lead to decreased slope stability (Crozier 2010; Basher *et al*. 2012).

Average snow cover in New Zealand is projected to decrease as a result of climate change (Mullan *et al*. 2008). This is expected to be especially noticeable below 1000m, with latest projections estimating a decrease of between 32 and 79% at 1000m elevation and 5–50% at 2000 metres by 2090 under the A1B climate scenario (similar to RCP6.0). Snow days per year are projected to reduce by 30 days or more by 2090 under RCP8.5 (Hendrikx *et al*. 2012; Hollis 2016).

While there is still considerable uncertainty in snow projections, this result is consistent with other studies in mid-latitudes and so it is expected that snow will be an increasing rarity in Christchurch through the twenty-first century with a corresponding decrease in any associated flooding impacts.

Hail

A major issue with the assessment of climate change on future hail occurrence is the inherent difficulty in modelling due to scale disparities and incomplete representation of hail-forming processes in climate models (Walsh, 2012). Different assumptions and methods to represent hail-forming processes have resulted in divergent results in climate change hail projections internationally, and so how climate change might affect hail is still a matter of great debate.

To date there has only been one study considering future projections of convective activity in New Zealand (Mullan *et al.* 2011). This study modelled various convective proxies, with CAPE and K-index indicating an increase in the frequency of severe weather over the next century but wind shear showing little trend. They concluded that "we would expect vigorous small-scale convective events to be more common and more intense in a future warmer climate" (Mullan *et al*. 2011, p73). However, care needs to be taken before using these results in a regional or local context due to issues of resolution as the CMIP3 global models used in the study (and in AR4) do not have sufficient resolution to make calculations of extreme weather in New Zealand (Mullan *et al.* 2011).

Wind

Extreme winds in Canterbury are projected to become more frequent over the next 80 years as a result of climate change (Ministry for the Environment 2016). This can be seen in projected changes in future synoptic weather patterns, where trough and south-westerly airflows (T & SW) are projected to become more frequent in winter but less frequent in summer, and zonal (westerly) airflows are projected to decrease in frequency in summer but increase in frequency in winter (Mullan *et al* 2011).

5.5 Key Extreme Weather Gaps Relevant to Flooding

5.5.1 Coastal Storm Gaps

There is a lack of analysis of the role that coastal storms with elevated sea levels has played in the FPF events within both the Avon Heathcote and the Styx catchments.

- The relationship between different types of storm events, wind direction and flooding is poorly understood.
- Unknown coincidence between storm surge, fluvial and pluvial flooding.

There has been no in-depth study done on the locations of low pressure centres with occurrences of storm surge in Christchurch.

5.5.2 Snow Gaps

There appears to be no documented research into links between local snowfall and flooding.

- Spatial variability of hail in Canterbury is poorly understood – this can be solved with a hail climatology based on radar reflectivity (e.g. Wapler 2017);
- No future hail projections as a result of climate change has been completed for Christchurch, Canterbury or New Zealand;
- There is no published research to date which establishes links between hail and synoptic weather in Christchurch.

5.5.3 Summary

Table 6-3 summarises the key gaps which are considered to be required to be filled to progress this project (shaded green), or other which are or interest for the wider understanding of Christchurch hazards, but are considered to not be vital for the progress of this project (shaded orange). Those required within this project are listed at the top of the table. Indicative budget estimates are classified according to: low <$20k, medium: $20 – $50k, high: > $50k.

Table 5-5 Gaps relevant to assessment of meteorological phenomena

Gap Description	Benefit if Addressed / Risk if not Addressed	Indicative Budget Estimate and Timescale Required
Analysis of extreme storm tide and wave environment • At present, no in-depth analysis of the occurrence of extreme wind and wave set up and storm surges is available for the Canterbury coast. • Investigation and modelling of influence of climate change on coastal storm intensity (waves and storm surge) for Canterbury	**Benefit**: This analysis represents a significant information gap that, if filled, would help inform us of the likelihood of coincidence and extent of exacerbation of coastal inundation and FPF events. **Risk**: Continued uncertainty on role extreme storm tide and waves on current and future FPF events	Budget Estimate: High Requirement: Within project
Coincidence between storm surge, fluvial and pluvial flooding • Current coastal storm analysis does not consider any coincidence between storm surge and FPF events.	**Benefit**: A better understanding of historic coincidence between different types of flooding, and determining of probability of co-incidence of these types of events. **Risk**: Current and future flood risk may be underestimated.	Budget Estimate: High Requirement: Within project
Study of mouth stability of Ihutai/Avon-Heathcote Estuary and Waimakariri mouth • Relationship of coastal storms, and FPF event son the stability of the distant ends of Brighton Spit and Brooklands Spit	**Benefit**: Better understanding of the processes involved and the likelihood of this occurring. **Risk**: Mitigation options relying on the current mouth configuration may not be assessed correctly.	Budget Estimate: High Requirement: Within project
Snowfall - flooding - synoptic weather interactions Currently there is no research which looks at the relationship between snowfall events and flooding in Christchurch. In addition, there is no in-depth study analysing synoptic weather situations with respect to flooding events and / or snow events for the Canterbury region.	**Benefit**: A more complete understanding of potential impacts of local snowfall events and associated flood risk **Risk**: That options considered do not appropriately consider or address snowfall impacts.	Budget Estimate: High Requirement: Outside project
Hail - flooding - synoptic weather interactions Currently there is no research which looks at the relationship between hail events and flooding in Christchurch or analyses the spatial variability of hail around Canterbury. In addition, there is no in-depth study analysing synoptic weather situations with respect to flooding events and / or hail events for the Canterbury region.	**Benefit**: A more complete understanding of potential impacts of hail events and associated flood risk **Risk**: That options considered do not appropriately consider or address hail impacts.	Budget Estimate: High Requirement: Outside project
Hail – future projections of hail under climate change There is low confidence in future projections of hail under climate change, and no projections to date for what might occur in Canterbury.	**Benefit**: A more complete understanding of potential impacts of hail events and associated flood risk and how these impacts might vary with climate change. **Risk**: That options considered do not appropriately consider or address future hail impacts.	Budget Estimate: High Requirement: Outside project

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6. Coastal Erosion and Inundation

6.1 Overview of Physical Coastal Processes

Coastal erosion is the process of wearing away and removing sediment and other materials from a particular coastal environment. On unconsolidated shores, such as along the majority of the study area's shorelines, this process results from an imbalance in the supply and export of materials to a particular section of coast or 'coastal cell'. Coast erosion can occur during everyday conditions, during high tide and storm conditions, and/or as a response to long-term changes in sea levels (PCE 2015). Coastal erosion may be expressed in terms of volume of material removed per length of coast per unit of time (e.g. m^3/m/year). Where it impacts the shoreline position, the term coastal erosion is often used synonymously with 'shoreline retreat', as in the case of the Tonkin & Taylor (2015) Christchurch coast assessment.

Coastal inundation is generally defined as flooding by the sea. It can occur at event time scales due to elevated sea levels and the action of wind and waves during extreme storms and/or extreme high tides (NIWA 2010), as well as more permanently and/or progressively due to changes in the balance between land elevations and sea level rise induced by climate cycles and trends, and due to more rapid land elevation adjustments such as with earthquakes (Beavan and Litchfield 2012; Hart *et al.* 2015). Areas affected by coastal inundation are flooded with seawater, bringing the dual challenges of water and salt, with wave and current induced effects like erosion also possible. Several studies have examined past and future predicted coastal inundation hazards within the Ihutai/Avon-Heathcote Estuary (Lamb 1997 ; CRC 2005 ; Tonkin & Taylor 1999 , 2013 , 2015 ; CCC 2014 ; Allen *et al*. 2014), while other broadly relevant studies have investigated storm surges along the east coast of New Zealand (Heath 1979 ; Bell *et al*. 2000 ; Thiebaut *et al.* 2009 ; Goring 1995 ; Goring and Bell 1995 , Goring *et al.* 2011).

6.2 Influence of Long-Term Climate and Other Changes

6.2.1 Sea Level Rise

Long-term sea level rise rates in New Zealand (Hannah 2004; Bell 2012; Hannah and Bell 2012) are of concern in terms of both coastal erosion and coastal inundation hazards since elevated sea levels can directly inundate the coastal hinterlands of low-lying cites, and hinder the drainage of low-lying areas such as all of the plains part of the study area. The latter effectively reduces river and estuary flushing capacities, and enhances tidal ingress and backwater effects in urban waterways like the Avon, Heathcote and Styx Rivers (e.g. MfE 2003); and elevates coastal groundwater levels, increasing soil moisture levels and reducing freeboard, and encouraging coastal erosion. Further, coastal inundation on extreme high tides with storm surges and/or large waves, is forecast to occur more frequently, severely and extensively in future as a result of ongoing Holocene adjustment sea level rise and land movement, combined with climate change induced accelerated sea level rise and increases in storm intensity. The model predictions described below in section 6.3 include long-term (50 and 100+ year) sea level predictions, with significant impacts showing at the 50 year timescale. However, there has not been any detailed assessment of magnitude of change in coastal storm intensity for the study area.

6.2.2 Sediment Supply

Any changes in the long term supply of sediment to the Christchurch coast are also of interest in this study since to the balance between sediment supply and removal (the sediment budget) determines whether or not the coast will accrete, remain stable or erode over the long term. Sediment-budget-driven shoreline change tends occur over, and last for, long timescales. Shoreline erosion hazards driven by the sediment budget can invoke long-term changes affecting the future viability of flood infrastructure as well as impacting flood affected coastal neighbourhoods. As such, any flooding infrastructure or management activities planned for areas predicted to be at risk of coastal erosion in future need to recognise the potential for coastal erosion and to have a planned response to the potential shoreline translation (e.g. Ramsay *et al.* 2012). Another implication is that the effects on the coastal sediment budget should be considered when evaluating any significant dredging operations or structures that limit the discharge of sediment from rivers to the coastal zone. Land use implications are also of key concern regarding coastal erosion/flooding multi-hazard cascades.

Earlier in the Holocene the city's coast was nourished by significant inputs of sediment from both the continental shelf and local river systems (Hart *et al*. 2008), but it is now believed that rivers are the main contributor to the contemporary coastal sediment budget. Several studies have examined a range of historical and future shoreline and/or sediment budget trends for the coast of wider Pegasus Bay (Campbell 1974), and Christchurch city (Kirk 1979 ; Cope *et al*. 1998 ; Hicks 1998 ; Duns 1995 ; Tonkin & Taylor 1999, 2013, 2015), while other studies have investigated sediment dynamics and shoreline trends within the Ihutai/Avon-Heathcote Estuary Ihutai (Macpherson 1978; Findlay and Kirk 1988; Hicks 1993; Burge 2007; Jupp 2007). Note that in order to fully understand coastal erosion hazards for the Christchurch city coast, it is necessary to overlay long-term shoreline trends with short-term dynamics due to storms and seasonal to inter-annual cycles in sediment supply and erosion processes. Coastal Storm effects on sea levels and waves are presented in Section 5 on Extreme Weather.

6.3 Christchurch Data and Modelling

Currently, the most relevant information concerning the past long-term and future predicted coastal erosion and coastal inundation hazards along the open coast and estuary margins of the study area is the 'Coastal Hazard Assessment: Stage 2' report by Tonkin & Taylor (2015), which includes maps of projected 2065 and 2115 erosion and inundation extent scenarios.

For historical long-term shoreline movements, Tonkin & Taylor (2015) using GIS analysis of five aerial photograph dates between 1941 and 2011 found that all of the Christchurch open coast shoreline from Waimairi Beach to the end of Brighton spit was accreting at rates between 0.1m/yr to 0.55m/yr, with the greatest rates of accretion being in the south shore area. ECan beach profiles over the same area since 1990 indicated similar results. There is no presentation of historical shoreline line movements for North of Waimairi Beach to the Waimakairiri River, Sumner, or the inside of the Ihutai/Avon-Heathcote Estuary, although there is similar coverage by aerial photographs and ECan beach profiles for the north coast and Sumner areas. The general conclusion from the historical analysis is that there is no current impact of coastal erosion on the magnitude and extent of FPF events, and that all potential future impacts will be driven by the effects of sea level rise. However, at Sumner during the March 2014 floods, the coastal protection structures prevented effective pluvial flood water drainage from this area; therefore it could be argued that the historical coastal erosion in Sumner, which resulted in the protection structures, has impacted the FPF flooding situation.

The Tonkin & Taylor (2015) assessment also does not include any assessment of the contribution of extreme storm tide and wave run-up the past inundation in the Ihutai/Avon-Heathcote Estuary or Brooklands Lagoon, at Sumner, or on the open coast. As indicated in Section 5, in the absence of other research, it is unclear what the current or past impacts of these coastal storm components has had on FPF events. New coastal erosion and inundation prediction maps are supposed to be available by mid-2017, upon completion of a revised Tonkin & Taylor coastal hazards assessment, including new erosion and inundation predictions for 2065 and 2120. The revised report and the associated map data will include a wider range of sediment budget and sea level rise scenarios, plus more extensive beach profile analyses. While the revised Tonkin & Taylor coastal hazards assessment data will provide the best starting point for this project's assessments of coastal erosion and inundation predictions, thorough analyses of the Christchurch coast sediment system and of the coastal storm component will remain as significant, high-priority information gaps. Note that a new central government guidance manual regarding coastal hazard predictions should also be available later in 2017.

6.3.1 Modelled Future Permanent Shoreline Erosion

The Tonkin & Taylor (2015) Coastal Hazard Assessment: Stage 2 report maps areas along the open coast and margins susceptible to future coastal erosion, which they termed Coastal Erosion Hazard Zones (CEHZ) for open coast and sheltered or 'harbour' environments (the latter including the Ihutai/Avon-Heathcote Estuary Ihutai). For both the open and 'harbour' coast (including the estuary), a building block approach was taken, including evaluation of short-term storm, dune stability, long-term shoreline, sediment budget, and future-predicted Bruun Rule type sea level rise response factors. For the estuary coast, a shoreline translation method involving translation of the Highest Astronomical Tide (HAT) contour with sea level rise was also applied. For the end of Brighton Spit south of Tern Street a "most landward shoreline position" approach was used due to the fluctuating nature of shoreline movements in this area.

The sea level projections used were extrapolated from Intergovernmental Panel on Climate Change (IPCC, 2014) Representative Concentration Pathway (RCP) 8.5 mid-range rise projections of 0.4m by 2065 and 1.0m by 2115. Probability distributions were constructed for each erosion component, and a Monte Carlo technique applied to generate a probability distribution for the resultant CEHZ within each coastal cell. The CEHZ were then mapped for both 2065 being a 'likely' erosion scenario (66% probability), and for 2115 for a 'potential' erosion scenario (5% probability). The resulting CEHZ maps are presented in Appendix A/2.

The Tonkin & Taylor (2015) report will shortly be superseded by a revised report, including revised maps for predicted coastal erosion in 2065 and 2120 under several IPCC (2014) sea level rise scenarios, and including a more detailed assessment of the net sediment budget for the Christchurch open coast based largely on analysis of the ~30 year beach profile records. This revised report is likely to indicate that the city's open coast sediment budget is smaller than suggested in earlier assessments, this new information being in line with recent beach profile analyses by ECan's staff (**Figure 6-1**).

Once the updated CEHZ maps are available from the revised Tonkin & Taylor report, the map presented in Appendix A2 should be superseded, and the new maps used for future analysis of multi-hazard risks.

Figure 6-1.Beach volumes for four selected Christchurch open-coast sites showing foreshore (blue), dune (orange) and total profile (white) sediment volumes recorded between 1990 and 2017 in ECAN surveys (Hart and Cope, 2017 , slide 37). Note that the beach profiles indicate that the growth in dune sediment volumes observed over this coast in recent times is not reflected in an equivalent increase in foreshore volumes. This indicates that the sediment budget of this coast is likely stable, and not accretionary as previously thought, and that gains in the dune part of the profile are a result of CCC dune recovery and management efforts, rather than due to a long-term trend. The outlook based on this data is that significant additional dune growth is unlikely since dunes prograde over the longer-term in response to foreshore accretion (e.g. McLean and Shen 2006).

6.3.2 Modelled Future Increased Coastal Inundation

The Tonkin & Taylor (2015) Coastal Hazard Assessment: Stage 2 report maps areas susceptible to future coastal inundation, which they termed Coastal Inundation Hazard Zones (CIHZ), for open coast and sheltered or 'harbour' environments, the latter category including the Ihutai/Avon-Heathcote Estuary. As for coastal erosion, CIHZ zones were mapped for both 2065 'likely' (66%) and 2115 'potential' (5%) scenarios, using actual and extrapolated IPCC (2014) RCP8.5 mid-range sea level rise projections of 0.4m by 2065and 1.0m by 2115.

In assessing the CIHZ for the Open Coast (including study areas between the mouth of the Waimakariri River and the far end of New Brighton spit), a simple building block 'bath tub' approach was used. Building block components comprised storm tide levels (1% & 2% AEP for 2065 and 2115 projections respectively), wave set up (using the Coastal Engineering Manual Method on 1% AEP wave heights from Tonkin & Taylor (1998)), and the above-mentioned IPCC (2014) sea level predictions. The resulting "bath tub" water levels for open coast locations are presented in **Table 6-1**.

Table 6-1 Coastal Inundation Hazard Components Values (Tonkin & Taylor, 2015)

Site	Timeframe	Storm Tide (m)	Wave Set-Up (m)	Sea Level Rise (m)	Total CIHZ Level (RL m)
New Brighton	2065	1.8	1.49	0.4	3.7
	2115	1.85	1.53	1.0	4.4
Sumner	2065	1.8	1.27	0.4	3.5
	2115	1.85	1.31	1.0	4.2
Taylors Mistake	2065	1.8	1.29	0.4	3.5
	2115	1.85	1.33	1.0	4.2
All levels reduced to Lyttelton Datum 1937 (LVD-1937)					

For the Ihutai/Avon-Heathcote Estuary, Brooklands Lagoon and Sumner, the CIHZ was modelled using a TUFLOW software method, which simulated the physics of the tides and sea levels to dynamically map inundation levels based on LiDAR derived post-earthquake topography and detailed estuary bed bathymetry survey data. This TUFLOW modelling did not include river base flows, or the effects of coincident rainfall, the inclusion of which might have increased the extent of predicted inundation. For both the open-coast and estuary modelling, either 20 year old or worst case wind and wave set up were used, since no recent in-depth analysis of the occurrence of extreme wind and wave set up and storm surges is available for the Canterbury coast. The latter would be a useful future investigation to complete, particularly if it were to include correlation analyses of the relationships between storm surge in and outside of the Ihutai/Avon-Heathcote Estuary and in Christchurch's urban river catchments. In this project, we have used the areas predicted by Tonkin & Taylor (2015) to be affected by coastal inundation hazards by 2065 and 2115. This map is presented in Appendix A/3. It is noted that there are some inconsistences of the inundation areas for the estuaries and rivers between the areas mapped by the coastal methodology used by Tonkin & Taylor (2015) and land based models used by the city in flood modelling. It is assumed that these inconsistencies will be resolved between the revised Tonkin & Taylor coastal hazard assessment and the City wide modelling, both due to be released in 2017.

Of significance, low-lying areas of the catchments and river channels that discharge into the estuaries are highly vulnerable to coastal inundation since elevated ocean and estuary water levels can block the drainage of inland systems, thereby compounding any fluvial and/or pluvial flood hazard event. Coastal inundation can also overwhelm stormwater and other drainage network components, meaning that their design capacity should consider the effects of coastal inundation.

6.3.3 Model Limitations

As indicated earlier, the revised Tonkin & Taylor report (due to be published mid 2017) will form the best available source of data for quantifying coastal erosion and coastal inundation hazards extents. This report will include robust probability analyses for these individual hazard occurrences at two future timescales. A significant related gap exists, however, in that no in-depth analysis of the occurrence of extreme wind and wave set up and storm surges is presently available for the Canterbury coast. This gap needs to be filled, along with the gap in our understanding of the weather patterns associated with pluvial and fluvial flooding across the city before a robust multi-hazard probability analysis of the coincidence of coastal inundation and urban flooding can be undertaken.

In addition, current river sediment supply and sediment budget data for Christchurch beaches are out of date and inadequate. The best available source of data will again be the Tonkin & Taylor revised report, which will include some probability models for the open coast beach sediment budget. Future stasis or reductions in Waimakariri River sediment supply rates are predicted to be associated with open-coast shoreline erosion at varying rates between the northern and southern extends of the project study area, over timescales of 50 to 100+ years, yet it is difficult to be more certain about the potential for changes in these rates in the absence of an accurate past and future sediment budgets. Shoreline erosion can directly affect the future viability of flood infrastructure as well as impacting the future resilience of flood affected coastal neighbourhoods. Effects on the coastal sediment budget need to be considered when evaluating significant dredging operations or structures that limit the discharge of sediment from rivers to the coastal zone. Land use implications are also of key concern regarding coastal erosion/flooding multi-hazard cascades. The river supply and beach sediment budget are significant, high priority gaps affecting this project. There is also a gap in the analysis of beach volumes and sediment budgets across the southern part of the study area, including Sumner.

6.4 Interactions between Future Coastal Erosion and Inundation and Flooding Events

An important distinction is made between coastal inundation and coastal erosion in terms of the potential impacts on affected land and assets, including flood infrastructure, and the implications for acceptance, adaptation, mitigation, and/or modification options. That is, responding to inundation may focus on structure design and/or building elevations to mitigate periodic hazard events, whereas with erosion there is a permanent loss of land hence mitigation measures are limited to either protection or retreat.

Of significance for the Christchurch coast study area, the Tonkin & Taylor (2015) predictions indicate that shorelines will erode and/or retreat considerably within 100 years along parts of the open coast between the mouth of the Waimakariri and the end of New Brighton Spit and within 50 years around the Ihutai/Avon-Heathcote Estuary and the lower Avon River reaches. This has implications for the siting of drainage and flood infrastructure in these areas as well as in terms of the need to manage flooding after the point when these areas are no longer deemed ‘terrestrial’.

Areas where rivers or creeks meet the sea are more vulnerable to coastal inundation since high seas can cause the rivers to back up inland. Within the Christchurch context, this includes the Ihutai/Avon-Heathcote Estuary and Brooklands Lagoon. Coastal inundation can also cause stormwater and drainage network components to be overwhelmed (e.g. Sumner) and may render river dredging options ineffective, since this can facilitate seawater intrusion future upriver where sea level are high relative to land and river levels (Goldsmith *et al.* 2015; Hart and Hawke 2016).

6.4.1 Co-incidences and Cascades

Although the further long-term coastal erosion and inundation projections includes short-term storm erosion and 1% AEP storm tides respectively, the impacts are of these riding on a higher sea level from climate change rather than the individual erosion and inundation events. Therefore the co-incidence and cascade effects on FPF events are considered together as a FPF event occurring with the future shoreline retreat and increased sea levels having already occurred. Such a cascade is likely to trigger similar process response interactions as the co-incidence of coastal storms with a FPF event. As outlined in Section 5.3 these include the following. However, these response triggers are going to occur more frequently and with greater consequences than with coastal storms under current sea levels.

- Direct inundation with extreme storm tide levels in the Ihutai/Avon-Heathcote Estuary, Brooklands Lagoon, and the lower reaches of Avon, Heathcote and Styx Rivers, and low coastal areas at Sumner.
- Extreme storm tide levels in Ihutai/Avon-Heathcote Estuary and Brooklands Lagoon producing flood backwater effects that restricts flood discharge, hence result flooding in these areas and lower river channels.

- Wave run-up on the Ihutai/Avon-Heathcote Estuary and Brooklands Lagoon resulting in inundation and erosion of shoreline fringe in these areas.
- Potential dune breaches resulting in surface flooding on open coast fringe, particularly where there are existing gaps in the dunes (e.g. South Brighton, New Brighton), with additional water flow into the Brighton Spit stormwater network and ultimately into the Ihutai/Avon-Heathcote Estuary. A lesser potential for dune breaches on Brooklands Spit
- Potential mouth migration/instability associated with erosion of far ends of Brighton and Brooklands Spits. This is also linked to climate change impacts on sediment supply and transport.

Additional effects from the long-term changes, not experienced in current coastal storms include:

- Increases in groundwater levels (covered in Section 9).
- Potential reduction in estuary and lower river channel stopbank stability with increased water levels.
- Potential increase in lower river bank instability with distance of increased salt water wedge intrusion up the river channels.

Based on above discussions, the anticipated likelihood of the cascade and the consequences for exacerbating flooding are summarised in **Table 6-2.**

Table 6-2 Anticipated Co-incidence/Cascade Likelihoods and Consequences of Future coastal Erosion and Inundation with Christchurch FPF events

Interaction with FPF Events	Future Coastal Erosion	Future Coastal Inundation
Co-incidence/Cascade Likelihood	High	High
Physical Impact Permanence	High	High
Consequence for exacerbating flooding	High	High

6.5 Key Coastal Process Knowledge Gaps Relevant to Flooding

Table 6-3 summarises key gaps which are considered to be required to be filled to progress this project (shaded green), or other which are or interest for the wider understanding of Christchurch hazards, but are considered to not be vital for the progress of this project (shaded orange). Those required within this project are listed at the top of the table. Indicative budget estimates are classified according to: low <$20k, medium: $20 – $50k, high: >$50k.

Table 6-3 Gaps relevant to assessment of coastal erosion and inundation

Gap Description	Benefit if Addressed / Risk if not Addressed	Indicative Budget Estimate and Timescale Required
Analysis of extreme tide and wave environment At present, no in-depth analysis of the occurrence of extreme wind and wave set up and storm surges is available for the Canterbury coast, including neither past analyses nor future predictions.	**Benefit**: This analysis represents a significant information gap that, if filled, would help inform us of the likelihood of coincidence and extent of exacerbation of coastal inundation and fluvial/ pluvial flood events.	Budget Estimate: Medium Requirement: Within project

Gap Description	Benefit if Addressed / Risk if not Addressed	Indicative Budget Estimate and Timescale Required
<u>Changes in future coastal erosion and inundation extents with changes in climate</u> The revised Tonkin & Taylor report will provide the best-available analysis of the future predicted extents of sea level rise induced inundation for Christchurch's coast. Mapping should be updated following Council-commissioned revised Tonkin & Taylor report.	**Benefit**: More robust coastal erosion and inundation prediction maps will inform decisions around flood management areas, and infrastructure design standards and locations, in Stage 3 of this project.	Budget Estimate: Already underway (T&T project) Requirement: Within project
<u>Changes in future coastal erosion and inundation extents with changes in sediment budgets</u> Current river sediment supply and sediment budget data for Christchurch beaches are out of date and inadequate. The river supply and beach sediment budget are significant, high priority gaps affecting this project. There is also a gap in the analysis of beach volumes and sediment budgets across the southern part of the study area, including Sumner.	**Benefit**: More robust coastal erosion prediction maps would inform decisions around flood management areas, and infrastructure design standards and locations, in Stage 3 of this project.	Budget Estimate: Medium to High Requirement: Within project

6.6 Coastal Erosion and Inundation References

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7. Tsunami

7.1 Overview of Tsunami Physical Processes

Tsunamis are displacement waves, created when a large volume of ocean or lake water is suddenly displaced by earthquakes, volcanic eruptions, terrestrial or underwater landslides, or meteorite impacts. Tsunami waves have long wave lengths and low amplitudes in deep waters with their amplitudes growing during shoaling in shallow nearshore environments. The extent of inundation, erosion and other kinds of damage experienced in a particular event is a function not only of the wave characteristics (e.g. velocities, amplitudes, number and timing of large waves), but also of tidal and meteorological conditions (storm surge, river levels), and of nearshore, beach backshore and river topography (Hart and Knight 2009).

Tsunamis are generally classified by the travel time from their source to the effected shoreline. The three common classifications being:

- Distant source tsunamis: Generated remotely from the receiving shoreline with a travel time of more than 3 hours. For Canterbury the major source of a distant tsunami is an subduction earthquake on the coast of Peru (Power 2013), which was the source of the 1868 and 1877 earthquakes that produced tsunamis affecting the whole east coast of New Zealand (Lane *et al.,* 2014). Other remote sources for New Zealand include the Chilean coast of South America, the Alaska-Aleutian margin, Japan, and the South Pacific subduction zones around the Solomon Islands and the Tonga-Kermadec Trench (Power 2013). The numerical modelling of the effect of these earthquakes on tsunami impacts in New Zealand involves modelling the tsunami at source and its travel across the deep water Pacific Ocean, and then using a second model to stimulate propagate across the continental shelf and inundation around the shoreline.
- Regional source tsunamis: Generated within 1-3 hour travel time to the shore. For Canterbury regional sources were considered to be the Hikurangi subduction Zone and the Wairarapa Fault (Kohout *et al*, 2015). The numerical modelling of these tsunamis is similar to distant tsunamis, although may be undertaken using a local model to stimulate propagation across the continental shelf and inundation around the shoreline.
- Local source tsunamis: Tsunamis with a travel time of less than hour to the receiving shoreline, occurring from the seabed rupture of local earthquake faults or submarine landslides. The recent North Canterbury-Kaikoura earthquakes in November 2016 can be considered as a local source for Christchurch tsunamis.

7.2 Christchurch Data and Modelling

7.2.1 Distant Source Tsunamis

Historical Events

Major distant source tsunamis experienced on the Christchurch coast from South American earthquakes include Aug 1868, May 1877, May 1960 and Feb 2010. Large sea level disturbances were also experienced in August 1883 as the result of a rissaga or meterological tsunami (i.e. tsunami-like waves generated by meteorological or atmospheric disturbances) generated by the Krakatau volcanic eruption. Data on the actual tsunami levels in Christchurch in these events is presented in **Table 7-1**(source NZ tsunami database), together with the magnitude of the generating earthquake and the corresponding tsunami height observations from the Lyttelton tidal gauge. The data is limited due to a lack of observations for events in the 1800's and lack of recorded measurements for events in the 1900's and 2000's events, and that the probabilities for the tsunamis is not available. It is notable from the limited data in the Table that tsunami water levels in Lyttelton are generally much higher than within Christchurch city, and there is no consistent co-relation between the heights in the two locations.

Table 7-1 Historical Tsunami levels for Christchurch and Lyttelton. Note that tsunami wave run-up levels are much higher in embayments like Lyttelton Harbour than in open coast environments due to wave amplification, reflection and resonance.

Tsunami Date	Source and magnitude(1) of Earthquake	Christchurch Tsunami water level (m > SWL)	Lyttelton Tsunami water level (m > SWL)
15 Aug 1868	~M9.1 Southern Peru/northern Chile	Christchurch 0.5m	7.60m(2)
11 May 1877	~M9 northern Chile	Waimakariri River 1.0m Avon River 0.90m	0.90m
28 Aug 1883	Krakatau eruption		1.80m
23 May 1960	Mw9.4-9.6 Central Chile		4.60m(2)
28 Feb 2010	Mw8.8 Central Chile	Sumner 0.4m	0.95m
Notes	(1) Magnitudes as given by Power (2013) (2) Max tsunami wave occurred at low tide so inundation impacts limited compared if occurred at higher tide.		

Power (2013) also summarises the data from the NZ paleotsunami database (Goff *et al* (2010) which includes at least one deposit at an elevation of up to 5m from an earthquake event dated AD1300-1450.

The lifetimes of the above historical tsunamis are not defined, but Power (2013) presents the results of a Monte-Carlo modelling process to estimate maximum tsunami heights expected over specified time intervals for 20km long sections of the New Zealand coast and size of the earthquake required to generate such an event at each source. The resulting graph for the probabilities of Christchurch Tsunamis (e.g. Godley Heads to north of Waimakariri River) is presented in **Figure 7-1**, with confidence levels from 16% to 84%.

The graph indicates that the largest observed tsunami in Christchurch (1877) had a probability of less than 100 years, and that if the paleotsunami had an amplitude of 5m, the probability was likely to be in the range 1 in 150-400 years with a certainty of 16-84%. Conversely, a 1 in 500 year tsunami has an 84% probability of being in the range 5.4m to 8m. The earthquake magnitude required to produce a 500 year 50th percentile tsunami of 6.5m at Christchurch is given at Power (2013) as being 9.28Mw if located on the coast of Peru and 9.55Mw if located on the coast of Chile.

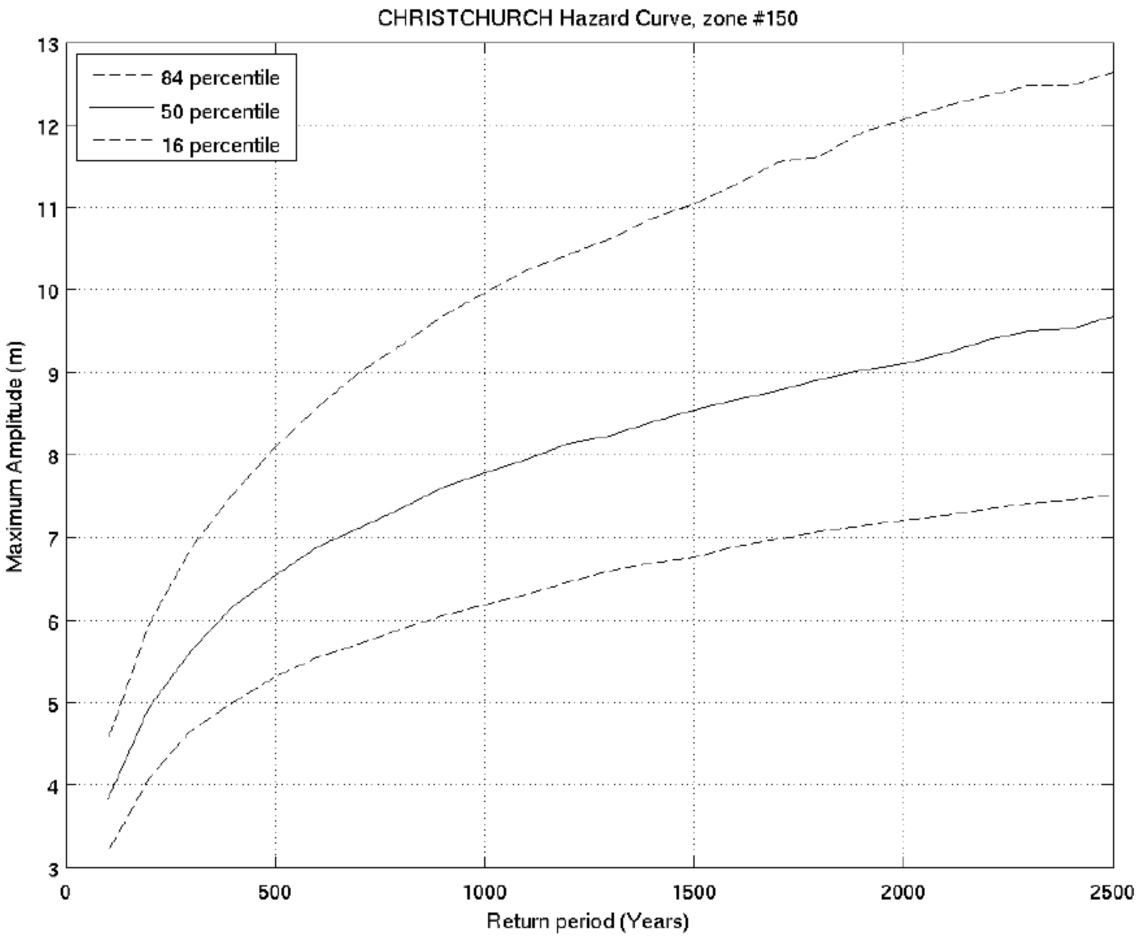

Figure 7-1 Power (2013) Figure 6.9: Tsunami hazard curve for Christchurch (Lane et al. 2014)

Christchurch Modelling

Lane *et al* (2014) presents the results of modelling of the inundation to selected Canterbury coastal areas including Christchurch City from distant source tsunami generated by an earthquake along the coast of southern Peru / northern Chile. This was an update from earlier modelling (Gillibrand *et al*, 2011) to incorporate changes in the land levels post the CES. The scenario modelled was a 2500 year probability event at 84 percentile confidence level from Power (2013) with a maximum tsunami amplitude close to at shore of 12.63m for isolated areas in Pegasus Bay. The corresponding earthquake magnitude required to produce this sized tsunami is given as Mw9.485 (Lane *et al* 2014). This “maximum creditable scenario” is what is recommended to be used for evacuation and emergency management planning rather than for land use and infrastructure planning.

The inundation modelling was undertaken using the hydrodynamic model RiCOM (River & Coastal Ocean Model), for which Lane *et al* (2014) notes that research has shown to adequately model tsunami inundation in the case of non-breaking waves. As a hydrodynamic model, the resulting inundation levels take into account friction effects of water flow over land, hence provide a better estimate of inundation depths than a “bath tub” modelling approach. The tsunami waves were modelled to arrive to co-incidence with MWHS tide levels and a quiescent sea state. An irregular, unstructured bathymetric grid resolution of 500m was used approaching the coast, and cut down to 10-20m resolution at the shore to match the land topography grid obtained from 2012 ECan LIDAR data. For the North and New Brighton sea walls, the modelling assumed a “walls down” situation.

The model outputs included:

- Maximum wave heights relative to MSL.
- Spatial data of depth and extent of inundation for the maximum tsunami arriving at MHWS.

- Spatial data of the maximum flow speed over land for the above maximum wave.

The inundation mapping for Christchurch from Lane *et al* (2014) is presented in Appendix A/4.

In summary the map shows that model results are that many land areas in New Brighton, South Shore, Redcliffs, Sumner and Taylor's Mistake are inundated to over 2.5 m . Bexley, the shoreward part of North New Brighton, Ferrymead and McCormack's Bay are also severely inundated in this magnitude tsunami arriving at MHWS water levels, with the tide contributing around 1.3 m to the water level. Flow speeds of over 5 m/s are predicted around the mouth of Ihutai/Avon-Heathcote Estuary, which have the potential to scour the inlet mouth, the distant end of Brighton Spit, and the toe of coastal walls around this part of the estuary.

Model Limitations

Limitations to the existing model include;

- No account taken of water levels in the Avon, Heathcote and Waimakariri Rivers. The consequence of this is that the modelling under predicts tsunami levels in these areas.
- There is no ability to take account of the potential morphology changes to the mouths and lower channels of the Ihutai/Avon-Heathcote Estuary and Waimakariri River/ Brooklands Lagoon as a result of tsunami induced scour, such as erosion of the distant end of Brighton Spit. International literature suggests that scour is most likely on the backwash phase of the tsunami as water rushes back to the sea. Changes in the mouth morphology would result in large changes to the volume of water able to enter the estuary or lagoon in normal and storm tide conditions.
- Similarly on the coastal dunes, the current modelling does not account for any scour of existing low spots which may result in breaches of the dune barrier, adding additional water into the drainage network.
- No account of scour or erosion of coastal or river protection works in the Ihutai/Avon-Heathcote Estuary or lower River channels of the rivers including the Waimakariri.
- No account of rising sea level on the tsunami inundation projections.

Some of these limitations have recently been addressed by updated NIWA modelling (Lane *at el.* 2017) which includes the following modifications:

- Incorporating lower river channel bathymetry and water levels associated with close to the mean average flow in each of the river systems (1m^3/s in the Avon and Heathcote, 60m^3/s in the Waimakariri). The incorporation of the bathymetry for the lower Waimakariri River included substantial channel depth, which had a large effect on the amount of tsunami water able to enter this system (Emily Lane, *pers com*)
- Scour of the mouth of estuary due to high tsunami velocities. The amount of modification to the size of the inlet was based on the assumptions made in Lamb (1997) that the width and depth of the entrance channel will increase by 20% each, giving an overall increase of 44% on the cross-sectional area of the entrance to the estuary.
- Incorporate breach of the coastal dunes in five locations where there are current low spots in the dunes (Caspian-Heron Streets, Torea-Tern Streets, South Brighton surf club, Neptune Place North Waimairi, and the far end of Brighton Spit). The depth of the breach was assumed to be from the 2m contour on the seaward side to dune base level at the landward toe.

However the model still does not account for any sea level rise, the effects of structures on ability of tsunami inundation water to return to the sea, or have the ability to deal with temporal geomorphic response to scour from increased tsunami water levels. The modelling also still does not address tsunami levels less that those generated in a 1:2500 year event.

7.2.2 Regional Source Tsunamis

Historical Events

The only record of a significant regional tsunami being experienced on the Christchurch coast is of a 1.25m bore travelling up the Avon River in Jan 1855, generated by a landslide on the west Wairarapa coast as the result of an Mw 8 magnitude earthquake. More recent region tsunamis such as Tonga 2006 and Samoa 2009 resulted in tsunamis of less than 0.2m at Sumner.

Christchurch Modelling

Kohout *et al.* (2015) presents the results of modelling of the inundation to selected Canterbury coastal areas including Christchurch City from regional tsunami scenarios resulting from a Hikurangi Subduction Zone earthquake and a Wairarapa Fault earthquake. The scenario modelled was an assumed “worst case” of a 1 in 2500 year tsunami with an 84% level of confidence. The corresponding earthquake magnitudes were Mw 9 for the Hikurangi Subduction zone event, Mw 8.6 m for the Wairarapa Fault event and Mw 9.15 for an event rupturing both faults simultaneously.

The inundation modelling was undertaken using two hydrodynamic models:

- RiCOM, as outlined above for the distant source tsunami model, using the same fixed bathymetric and topography grids.
- Basilisk model, a flexible mesh model which allows the mesh to adaptively refine or coarsen to follow the tsunami wave crests or any other features which the model is required to resolve. Non-linear shallow water equations are used within the model to solve the tsunami inundation. Kohout *et al.* (2015)reported that the model has been validated against tsunami test-cases and used to model the Indian Ocean (2004) and Tohoku-oki (2011) tsunamis.

As with the distant source tsunami, the regional source tsunami waves were modelled to arrive to co-incidence with MWHS tide levels and a quiescent sea state.

The model outputs showed that the magnitude and effects a tsunami sourced from the Hikurangi Subduction zone fault would be greater than a Wairarapa Fault source. The effects of a combined fault rupture were modelled to be similar to those from a Hikurangi Subduction zone fault. The outputs for the Hikurangi Subduction zone fault source included:

- Maximum wave heights relative to MSL: 1-3m for the open Christchurch coast and up to 1m on the Ihutai/Avon-Heathcote Estuary.
- Spatial data of depth and extent of inundation for the maximum tsunami arriving at MHWS, taken to 1.2m above LVD 1937: Up to 2.5 m at the mouth of the Waimakariri River and 2m at South shore, Moncks Bay and Clifton Bay.
- Spatial data of the maximum flow speed over land for the above maximum wave: Maximum of 2m/s at the Waimakariri mouth and over 3m/s around the mouth of the Ihutai/Avon-Heathcote Estuary.

The inundation mapping for Christchurch from Kohout *et al.* (2015) is presented in Appendix A/5.

Model Limitations

The model limitations are generally the same as for the distant tsunami source. However, an additional limitation is that the earthquake source was chosen for maximum tsunami wave amplitude at Kaikoura, which due to the influence of the Chatham Rise on refraction of the tsunami, may not have produced the largest possible tsunami for Christchurch (Emily Lane *pers com*).

There are no plans to update the regional tsunami hazard modelling to address these limitations.

7.2.3 Local Tsunami Source

Historical Events

There is no evidence of tsunamis generated by local offshore earthquakes or landslides causing inundation along the Christchurch coast. While the recent North Canterbury-Kaikoura Earthquakes in November 2016 generated a local tsunami with maximum run-up elevations up to 4m above MSL in Little Pigeon Bay on the

Banks Peninsula, the maximum tsunami amplitude recorded on the Sea Level recorder at Sumner was less than 0.5m.

Christchurch Modelling

Up until the CES in 2010-2011 the common held view was that there was little risk for Christchurch from a locally generated tsunami. Modelling of the an offshore rupture on the Kekerengu Bank Fault and a Kaikoura Canyon landslide event (Walters *pers com* 2003, 2004) focussed on tsunami inundation on the Kaikoura coast north of Orari, and off shore faults in Pegasus Bay were little known, or not considered likely to generate tsunamis.

Following the CES, NIWA undertook seismic surveying of the seabed of Pegasus Bay to improve the understanding faulting and possibility of tsunami generation in this area. Although the surveys revealed previously unknown offshore faults east of Kaiapoi, the findings relevant to tsunami generations were (Barnes (2012):

- In North Canterbury, part of the ancient fault system has been reactivated and overprinted by active deformation occurring as part of the Pacific-Australian plate boundary zone. This deformation extends up to 30 km offshore beneath Pegasus Bay, and includes at least 11 major faults, with evidence of renewed activity mainly in the last 1 million years.
- Most of this faulting is concentrated beneath the northern part of the bay, but newly-recognised, very weak deformation appears to extend southward to the northern coast of Banks Peninsula.
- The major faults range in length from about 10 to 38 km, and are thought to be capable of producing earthquakes of magnitude M6.4 to M7.2. Estimated vertical rates of faulting are very low in the north of the bay (~0.05-0.28 mm/yr), and extremely low (<0.01-0.07 mm/yr) in the south of the bay. These rates indicate that earthquakes are likely to have very long recurrence intervals, of the order of 10,000 years in the north, to perhaps several tens of thousands of years in the south.

No modelling of tsunami generation from these faults has been undertaken, but information from GNS science suggests that tsunami amplitudes would not be expected to exceed 2m (Dr Emily Lane, tsunami modeller, NIWA, per com. May 2017).

NIWA undertook seabed seismic surveying following the North Canterbury-Kaikoura Earthquakes in Nov 2016, which indicated that a large mudslide had occurred in the Kaikoura canyon as a result of the earthquakes. Preliminary analysis also indicated that the likelihood of a damaging tsunami being generated from landslides in the canyon had not increased due to the earthquake, and may be lower than previously thought, (Stuff online article Feb 27, 2017).

7.3 Interactions between Tsunami and Flooding

7.3.1 Co-incidences

Tsunami and FPF events are independent events, so the probability co-incidence between the event is the product of the probabilities of the individual events. Hence, the co-incidence of the mapped tsunami inundation (i.e.1;2500 years ARI), with the mapped FPF scenario (i.e. 1:500 years ARI) would have a probability in excess of 1 in 1 million years, therefore the co-incidence of such events is not considered further.

For Christchurch tsunami events with amplitudes around the maximum observed in the last 150 years (e.g. up to 1m), the likely process – response interactions are considered to be similar to those experienced in coastal storm events. However, the probability of this co-incidence is still in the order of 1:50,000 years.

7.3.2 Cascade

Due to the low probability of a significant tsunami event, the likelihood of cascade of such a tsunami and a FPF event is also extremely low. However, should a tsunami event with sufficient energy to generate geomorphic change in the mouth of the Estuary, breach the sand dunes and scour out infrastructure around the estuary margins occur, it could result in the following potential impacts for any subsequent FPF event.

- Increased high tide water levels in the Estuary due to increased tidal prism from earlier tsunami scour of end of Brighton spit and bed of entrance channel.
- Potential increased flooding around the margins of the estuary and lower river channels due to failure of protection walls and stopbanks in tsunami.

It is considered that tsunami events of sufficient magnitude and energy to create the above impacts are most likely to be distant or regional events, with current knowledge being that locally generated events are less likely to be large enough to cause these impacts. However, given the current paucity of information on the local source tsunami event likelihood and nature, plus the lack of warning time expected in any such events, this should be examined further.

Similarly a significant tsunami event prior to coastal storm events could have the same impacts on coastal inundation magnitudes and extents.

7.3.3 Summary

Based on the above discussions, the anticipated likelihood of co-incidence and cascades, and their consequences for exacerbating flooding are presented in **Table 7-2**.

Table 7-2 Summary of Anticipated Co-incidence and Cascade impacts for Tsunami Events and Christchurch FPF Events

Interaction with FPF Events	Significant Distant Source Tsunami	Significant Regional Source Tsunami	Significant Local Source Tsunami
Co-incidence Likelihood	**Very Low**	**Very Low**	**Very Low**
Co-incidence Consequence for exacerbating flooding	**Very High**	**High**	**High**
Cascade Likelihood	**Low**	**Low**	**Low**
Cascade Physical Impact Permanence	**High** Estuary/River mouth Estuary infrastructure	**Moderate** Less likelihood of permanent impacts	**Uncertain**
Cascade Consequence for exacerbating flooding	**High** Estuary/River mouth Estuary infrastructure	**Moderate**	**Uncertain**

7.4 Influence of Long-Term Climate Changes

7.4.1 Sea Level Rise

Changes in long term sea level will have no impact on the generation of tsunamis, hence have no effect on the likelihood of co-incidence or cascade of events. However sea level rise will increase the effect of tsunami events, due to increasing the underlying water level that the tsunami is superimposed on. For example, a tsunami arriving at low tide in 100 years with a sea level rise of 1m, will have a similar total water level to the same amplitude tsunami arriving at MHWS today. Hence the consequence for exacerbation of flooding will increase with sea level rise.

7.4.2 Increased Groundwater levels

Associated with sea level rise will be increased coastal ground water levels. Any such changes may have a small potential effect on tsunami inundation due to a reduction in infiltration resulting in a slightly larger inundation footprint. It is difficult to quantify or model such changes.

7.4.3 Storm Intensity and Frequency

Due to the low co-incidence probability, and on influence of changes in storm intensity and frequency on tsunami generation, it is considered that future climate induced changes in these parameter will have no impact on the multi-hazard interactions between tsunamis and FPF events.

7.5 Key Tsunami Hazard Knowledge Gaps Relevant to Flooding

Table 6-3 summarises key gaps which are considered to be required to be filled to progress this project (shaded green), or other which are or interest for the wider understanding of Christchurch hazards, but are considered to not be vital for the progress of this project (shaded orange). Those required within this project are listed at the top of the table. Indicative budget estimates are classified according to: low <$20k, medium: $20 – $50k, high: > $50k.

Table 7-7-3 Gaps relevant to assessment of tsunami hazards

Gap Description	Benefit if Addressed / Risk if not Addressed	Indicative Budget Estimate and Timescale Required
Modelling of Tsunami inundation levels, areas and velocities at 100 and 500 year probabilities At present, no modelling of these probability events, has been undertaken, therefore it is not possible to assess the consequences of such events for FPF with any certainty.	**Benefit**: Comparable probabilities to other hazards, to allow more meaningful analysis across similar hazard frequencies **Risk**: Remain with tsunami hazards being considered at probabilities an order of magnitude higher that other hazard events	Budget Estimate: Medium to High (can be undertaken as one project) Requirement: Within project
Maximum creditable amplitude and inundation mapping of local generated tsunamis At present there is no knowledge on the level of local tsunami risk	**Benefit**: Remove uncertainty on the level of risk from such events **Risk**: Uncertainty remains, so impacts and risks may be underestimated	
Investigation of tsunami scour impacts • Geomorphic response modelling at the mouths of the Ihutai/Avon-Heathcote Estuary and Brooklands Lagoon • Infrastructure scour modelling around the margins of the estuary, and lower river channels, including impacts of structures on return flows.	**Benefit**: Remove uncertainty the magnitude of impacts of tsunami scour **Risk**: Uncertainty remains, so impacts and risks may be underestimated	
Mapping combined Tsunami and sea level Inundation Incorporating sea level rise into tsunami inundation mapping	**Benefit**: Consistency of mapping of future hazard risk	

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8. Earthquake and Liquefaction

8.1 Overview of Earthquake Physical Processes

Earthquakes represent the sudden release of stored elastic energy in the Earth's lithosphere, caused by its abrupt movement or fracturing along zones of pre-existing geological weakness, resulting in the generation of seismic waves (Smith and Petley 2009). Earthquakes induce ground changes that have implications for FPF hazards. In this report we examine three sets of recent earthquake data from the CES – peak ground acceleration, ground shaking intensities, and net vertical displacement – as well as relating the earthquake hazard to changes in liquefaction risk, mass movements and ground water elevations, all of which have implications for FPF hazards. However, apart from mapping known fault lines that could affect the Christchurch area and historical uplift/ subsidence rates. it is challenging to predict the likelihood of future earthquake hazards across a catchment such as the Ōpwāho Heathcote River, particularly when there may be additional fault systems that we are currently unware of.

8.2 Christchurch Data and Modelling

A review of earthquake hazards has been undertaken by Hart and Hawke (2016) as part of the Heathcote River Floodplain Management Plan (LDRP110). This information is summarised below along with information generated in the LDRP110 project through a geotechnical review of the likely land surface changes arising from future earthquakes. It should be noted that this information was gathered for and specifically assesses the Heathcote catchment only, with set boundaries and as such while it presents general information for the wider city is not a specific assessment for all the LDRP97 project areas. Therefore within this project further information has been gathered and mapped for specific earthquake hazards (liquefaction and vertical displacement) within the study area.

8.2.1 Earthquake Origins

Three classes of earthquakes have been identified as potential major hazards to the Christchurch area:

1. Close proximity (Christchurch), moderate size (Mw 5.0-6.5);
2. Regional (Canterbury Plains and Southern Alp Foothills), large size (Mw 7.0-7.5); and
3. Distant (Southern Alps), great size (around Mw 8.0).

It is currently impossible to predict exactly when, where and how future earthquakes will affect Christchurch. Despite these uncertainties, we do have an opportunity to conduct a retrogressive assessment of catchment area susceptibility to earthquake-related hazards based on data from the events listed in **Table 8-1**, while also acknowledging that the area might not behave in exactly the same manner during future events. The 22 February 2011 event, in particular, represented a severe event for the city, so might reasonably be used as a scenario for the purposes of this multi-hazards analysis.

Table 8-1 Canterbury Earthquakes Summary

Earthquake Event	Type	Mw	PGA (m/s/s)	PGA (%g)
Darfield 2 September 2010	Regional	7.1	0.12-0.5	0.4-12.8
Christchurch 22 February 2011	Close proximity	6.2	0.14-1.26	1.2-5
Kaikoura 14 November 2016	Distant	7.8	<0.1	1
Hope Fault (modelled)	Regional	7.1	0.6	6.1

Earthquake Event	Type	Mw	PGA (m/s/s)	PGA (%g)
Alpine fault (modelled)	Distant	8.2	0.78 0.6	8 6.1

8.2.2 Ground Shake

The 2010-11 earthquakes affecting Christchurch were unusual in their strong shaking relative to the size of the earthquake. Ground shaking was severe in both the Christchurch and Darfield events (**Table 8-1**), with vertical land movement in excess of 0.5-1 m occurring in parts of the Heathcote Catchment. In addition, shaking during these two events resulted in widespread liquefaction in Christchurch's eastern suburbs and along the Avon River. In comparison, the distant Kaikoura Earthquake of 14 November 2016 only resulted in a horizontal displacement of 0.02 cm within Christchurch, with little vertical displacement and no observed liquefaction within the city.

8.2.3 Vertical Land Displacement

The local portion of vertical elevation changes from 22 February 2011 to 13 June 2011 are represented in Maps A6a and A6b (**Appendix A**) and are based on vertical ground surface movement data, obtained from the Geotechnical Database. Map A6a shows the vertical displacement of the 22 February 2011 to 13 June 2011 earthquakes without the tectonic component. Map A6b shows the tectonic component of vertical ground displacements between 4 September 2010 and 13 June 2011. The main observed changes in each catchment were as follows:

- Lower Heathcote catchment – The majority of the catchment showed little change in elevation. The land surface did however lower in the order of 0.1 to 0.2m in an east-west line along Heathcote River and through Linwood area.
- Lower Avon catchment – The majority of the catchment had a reduction in elevation in the order of 0.1 to 0.2m.
- Estuary/South Shore catchment – Sumner and South Shore appeared to be little changed with a general reduction in the order of 0.1-0.2m in South Brighton and other areas around the lower Avon area of the estuary.
- Styx/Brooklands catchment – The majority of the catchment showed little change in elevation. Areas with a decrease in elevation were generally alongside the Styx River, in Northshore and Spencerville/land around Brooklands Lagoon.

8.2.4 Liquefaction

Maps A7a and A7b (**Appendix A**) present observed liquefaction from the September 2010 and February 2011 events (Map A7a) and the Technical Land Categories (Map A7b). It is considered that within this project the best indication of liquefaction risk is the Technical Land Categories (TC) as this indicates the risk across a range of studied events for all residential land parcels and is a repeatable prediction whereas the observed information is only relevant to the particular events that caused that liquefaction. In general there is correlation between these two maps. The key exception and an obvious gap is that TC categories only apply to residential land whereas liquefaction has clearly been observed in other land use areas. On the TC maps there is no TC1 land identified, as all of this category of land is outside of the extent of the mapped area. Therefore any land not classed as TC2 or TC3 is non-residential land and unclassified at present. The main observed liquefaction observations or mapped risk in each catchment were as follows:

- Lower Heathcote catchment – This catchment had liquefaction observed across much of the area especially focused on the lower catchment nearer to the river mouth/estuary. In much of the upper area of this catchment this also visually appears to correlates with the TC2 and TC3 land and especially the areas with greater amounts of TC3 land. However in the lower catchment there are large areas of non-residential land without a TC classification where liquefaction was clearly observed.

- Lower Avon catchment – There were large areas of liquefaction observed through this catchment covering the majority of the catchment with the exclusion of the coastal areas of Brighton and North Shore. The observed liquefaction visually appears to correlate with the TC3 and red zone land especially. As with other catchments there are numerous gaps due to non-residential land.
- Estuary/South Shore catchment – Liquefaction was generally observed around the estuary only within areas of Southshore, Redcliffs and around the waste water treatment plant and oxidation ponds. Within Redcliffs and Southshore this correlates with the TC3 land areas however there are large areas of unclassified non-residential land around the oxidation ponds.
- Styx/Brooklands catchment – This catchment has the least information available based on TC land categories and hence is the biggest gap in knowledge in terms of risk of liquefaction. The zoned areas are located in Brooklands (red zone) and Spencerville (TC3) whereas liquefaction was observed over a wide area.

8.2.5 Local Tsunami

As outlined in Section 7.2.3, local source tsunamis include those with a travel time of less than hour to the receiving shoreline, occurring from the seabed rupture of local earthquake faults or submarine landslides. The recent North Canterbury-Kaikoura earthquakes in November 2016 can be considered as a local source for Christchurch tsunamis. Little work has been done to predict potential tsunami generation from locally generated tsunamis. Therefore the magnitude and frequency of any risk and how it could impact on flooding hazards is not known and an identified gap for this project.

8.2.6 Hill slope Instability

Slope instability and mass movement in the form of rockfalls and debris flows occurred on the Port Hills during the CES, resulting in building damage, fatalities and evacuations. These have been extensively mapped and analysed highlighting areas prone to rockfall and at risk of cliff collapse. Evidence was also found of earthquake-triggered tunnel gully collapse in all Port Hills valleys. Follow-on effects of these slope instabilities are likely to occur in major future events, with the possibility that earthquake-triggered slope instabilities could affect tributaries in the Port Hills sub-catchments areas. With rockfalls and slip/sheet slope instability a known hazard for parts of the Port Hills, there is also the possibility of an earth/ rock dam and subsequent upstream ponding. Mass movement is further reviewed in Section 11 and presented in Map A9 (**Appendix A**).

8.3 Modelled Hazard Scenarios

Changes to land surfaces after predicted future earthquakes have been considered as part of LDRP110. The project had a task to “Develop future land surfaces to represent topography after predicted 1 in 250 and 1 in 2,500 year earthquake events” and to run the flood model with these new surfaces to understand the impact on flooding. Various methodologies were considered of ways to represent the changes that may occur in various earthquakes. This is reported in the LDRP110 memo titled “Methodology for Estimating Uplift and Subsidence within the Heathcote Catchment dated 24 February 2017 (Jacobs NZ Ltd, 2017). A review and analysis of possible methods and the available data was contained in that memo, and three approaches were proposed for consideration for modelling changes in the topography of the flood model from future earthquakes. One of the methods reviewed was that used by Beca (2016) in their South Brighton Floodplain Management study. This method was discounted for use in LDRP110 due to the large increase in scale required for CPT data and the high variability in soil conditions with the Heathcote catchment making the method complex and time consuming. The three approaches proposed for LDRP110 are summarised as follows:

1. **Scenario 1: The cumulative ground movement experienced across the catchment in the 2010 – 2011 Canterbury Earthquake Sequence occurs again.** This scenario involves altering the topography of the hydraulic model by uplifting the area towards the estuary by up to 400 mm and lowering the central section of the catchment by up to 150 mm. Hydraulically, this is expected to have a measurable impact in flood risk and the scenario will be clearly understood by those with experience of the CES. The ARI of this event is approximately 1 in 10,000 and this represents the impacts of a near-field earthquake.

2. **Scenario 2: The cumulative ground movement used in Scenario 1 is scaled linearly to predict tectonic uplift and subsidence in a future 1 in 250 and 1 in 2,500 ARI event.** Given only one data point, scaling the CES impacts is uncertain, but suggests that the maximum uplift in the Heathcote catchment will be 100 mm and maximum subsidence will be 40 mm in a 1 in 2,500 ARI event. Scaled movement in the 1 in 250 year event will therefore be up to 10 mm. The existing ground could be modified by the predicted movements in the 1 in 2,500 year event which may or may not have a measureable hydraulic impact. However, no measurable impact in flood risk is expected from the predicted movement in a 1 in 250 year event. As for Scenario 1, this represents the impacts of a near-field earthquake.

3. **Scenario 3: The ground subsidence associated with a far-field Alpine Fault earthquake is predicted for a 1 in 250 year event.** Removing the component of tectonic uplift experienced in the CES suggests that up to 0.2 m of subsidence and uplift occurred over areas of the catchment. Linearly scaling these CES impacts using the ARI of an Alpine Fault earthquake suggests that areas of the Heathcote catchment could experience up to 0.15 m of change in a 1 in 250 year event. However, these results are highly conservative (i.e. high magnitude of predicted movement) because the peak ground accelerations in the CES were up to an order of magnitude greater than anticipated in an Alpine Fault earthquake. The ground surface in the hydraulic model would be varied by up to 150 mm to represent the impact of a 1 in 250 ARI far-field earthquake; no predictions are made for a 1 in 2,500 ARI earthquake.

Scenario 1 was chosen to be modelled within the LDRP110 project and for this project it is suggested that consideration should be made of whether the LDRP110 methodology is still the most appropriate for all study areas within the multi-hazards project, or whether this gap in knowledge of the impacts of less frequent or different source events should be further addressed.

8.3.1 Model Limitations

The methodologies above are broad and based on vertical ground movement during the CES due to tectonic movement and co-seismic land movement and consideration of the CES as a single event. Any probability analysis assumes a linear relationship as there is only one CES to reference. The Alpine Fault methodology is also considered to be highly conservative (i.e. high magnitude of predicted movement) because the peak ground accelerations (PGAs) that resulted in the vertical ground movements in the CES were up to an order of magnitude greater the PGAs anticipated from an Alpine Fault earthquake.

A possible alternative scaling technique for less frequent of different source earthquake events may be to use PGA rather than event return period.

8.4 Process Interactions Relevant to Flood Events

There have been a number of studies focusing on various aspects of recent earthquake hazards and impacts in Christchurch, especially following the damaging CES, which included the 7.2 Mw Darfield earthquake on 4th September 2010, and the 6.4 Mw Christchurch earthquake on 22nd February 2011. Earthquake-related effects identified as having the potential to impact on flooding in the Heathcote catchment include tsunami; vertical ground displacement; liquefaction and Slope instability (Hart & Hawke 2017). Analysis of vertical ground displacement showed that the upper parts of the Heathcote catchment have been subjected to tectonic subsidence as a result of the earthquakes, but the lower sub-catchments uplifted. This has had the effect of reducing river gradients. Several studies have also focused on the impact of the earthquakes on flooding in the lower Avon catchment (Allen *et al.* 2014, Hart *et al.* 2015) and changes in the Avon-Heathcote Estuary (Measures et al. 2011).

These earthquake-induced land changes are considered to have substantially significantly increased the cities' flood risk, with the main factors contributing to the increased flood risk being the widespread tectonic and liquefaction-induced subsidence, alteration of water courses through bed heave, lateral spread of brooks, damage to vegetative cover and the influx of sediment load to water courses. In addition, lowering of surface elevations relative to water tables is likely to have increased the liquefaction and flood hazard.

The earthquake associated risks of vertical ground displacement and liquefaction susceptibility have historically affected, or are in future predicted to affect, all of the catchments in the study area. During the CES, these phenomena induced significant changes in the drainage systems, pipe networks, open waterways etc., including:

- Extensive vertical displacement and liquefaction induced damage to stormwater greyware (pipes, inlet, outlets, grates/sumps, paved roads, curbs and channels), which collectively reduced functionality of the stormwater system;
- Damage to the wastewater system, including cracked pipes, which helped to temporarily lower groundwater levels and increase stormwater drainage via the wastewater network on the one hand but which created a very significant pollution multi-hazard for FPF hazard on the other hand;
- Liquefaction induced horizontal rafting of river banks, uplift and sedimentation of river channel beds, and vertical displacement induced river gradient changes - processes which collectively affected river drainage capacities;
- Subsidence induced loss of soakage and infiltration capacities affecting detention and soakage basins, wetlands and vegetated swales and other unsealed earth surfaces;
- Vertical displacement induced changes in the drainage conductivity of the topography, with increased basinisation in mid-catchment areas and uplift hindering drainage to coastal environments in the lower catchment;
- Estuary subsidence (mainly around the Avon catchment margins), increasing both FPF and coastal inundation flood hazards in coastal catchment reaches;
- Estuary bed uplift (severe around the Heathcote margins, and partial around sections of the Avon catchment margins), reducing tidal prisms and increasing bed friction, thereby producing an overall reduction the waterbody's capacity to efficiently flush catchment floodwaters out to sea; and
- Vertical displacement and liquefaction induced loss of changes to estuarine and riverine ecosystems.

All of these possible effects, both direct and cascading, need to be considered when evaluating the present and future capacities of the FPF flood management systems.

8.4.1 Ground Shake

For ground shaking processes evidence exists of the magnitude of shaking experienced in past earthquakes. For future earthquakes there are also predictions of likely magnitudes of shaking for regional or distant sources. However ground shaking from local source earthquakes would be dependent on the exact location of the quake with respect to features and areas of interest.

The interactions between the ground shaking in a future earthquake and increased flood risk are fairly well known from recent events and include the damage to stormwater networks, channels and banks as noted above. However the exact degree and distribution of damage from a future quake is not clearly understood in a way that could be transferred into a hydraulic model scenario to understand changes to flooding impacts after a future earthquake event. This would require a high resolution consideration of damage to all elements of a stormwater network and drainage system that are represented in a model. While this is a gap in knowledge it is not considered that that this gap is of value to fill within the project as it may be able to be approximated by more simple assumptions.

8.4.2 Vertical Land Displacement

The mechanisms by which vertical land displacement can impact upon flood hazard are well understood from recent CES experiences. The challenge is in predicting the change in future quakes in a way that could be represented in a future modelled post-earthquake flood scenario. The CES information has been used within LDRP110 to predict future earthquake effects on land surface elevations as discussed in Section 8.3. This considered a variety of ways to predict future land surface changes from a range of local or more distant quakes with different uplift and subsidence mechanisms. There were a number of challenges to using certain methods and the end decision taken was to replicate the cumulative CES changes again.

This approach does leave a gap in knowledge regarding the impact of more frequent earthquake events or non-local source earthquake effects on flooding risks. For this project it is suggested that this gap still exists but consideration should be made of whether the LDRP110 methodology is still the most appropriate or whether this gap should be further addressed.

8.4.3 Liquefaction

Similar to other effects of earthquakes the impacts of the liquefaction on flood risk is well documented in terms of impacting on drainage infrastructure and waterways. What however is not known is how liquefaction will be distributed in future earthquakes of various types. The TC land categories that are available have notable gaps in information about vulnerability to liquefaction and there is therefore a gap in knowledge of how much liquefaction could occur in many areas. This liquefaction risk also has interactions with the groundwater hazard and with changes to groundwater driven by sea level rise. From discussions with Council it is known that further work is underway to quantify both changes to future groundwater levels and also on liquefaction risk. It is assumed that these studies will provide the necessary information to address this gap. As such no further work is recommended on quantifying liquefaction risk and liquefaction generation until the outputs of those projects are available and reviewed. This is timetabled to be in late 2017.

In terms of flood risk there is still however a gap, being that there is not a way to correlate TC land category and the amount of liquefaction that may be generated in a given source and magnitude quake to actual liquefaction impacts on drainage networks and waterbodies. While the work currently in progress may tell us where liquefaction could occur it is not anticipated to translate into predictions of an earthquake of a certain source and magnitude resulting in X amount of liquefaction impacting upon a number of drainage pipes by filling them to a certain level and also resulting in a one-off increased sedimentation of certain depth in river channels in future events. This is the information that would be needed to then be represented in hydraulic models to predict how flooding changes as a result of liquefaction driven mechanisms. This is therefore a gap at present in knowledge. The alternative is a scenario-based approach where pipes and waterways are assumed to be x% blocked.

8.4.4 Local Tsunami

As noted above there is limited information at present about the type and magnitude of tsunami waves that a local source earthquake could generate. A Tsunami could cause flooding itself depending on the size and state of tide or it could exacerbate a flood event if it were to occur at the same time. The likely impact would depend also on the size of any wave generated, the amount of storm surge and the height of the tide. Therefore the primary gap at present is that of ‘what height tsunami could a local earthquake wave generate and at what probability would interact this with flooding and tides?’

8.4.5 Hillslope Instability

Earthquake induced hillslope instabilities predominantly relate to rockfall and slip/sheet landslides. The potential for one to block a Port Hills stream and cause upstream ponding has been identified. The exact location and size of any blockage / ponding in any given future earthquake scenario is not known. It is considered that within an urban environment such as Christchurch any blockage big enough to cause a potential flood hazard would be identified quickly after an earthquake and addressed as a priority by Council engineers. As such the chance of it then causing an issue in a flood event is likely to be low. Within this study the majority of the catchment areas are in flatter areas of the city with only small areas on the hills around the estuary and Sumner where rockfall could occur. Hillslope stabilisation works on Peacocks Gallop has also been completed. Therefore it is not considered that further work needs to be undertaken.

8.4.6 Summary

Based on the above discussions, the anticipated likelihood of co-incidence and cascades, and their consequences for exacerbating flooding are presented in **Table 8-3**.

Table 8-2 Summary of Anticipated Co-incidence and Cascade impacts for Earthquake and Liquefaction

Interaction with FPF Events	Distant Earthquake	Regional Earthquake	Local Earthquake
Co-incidence Likelihood	Very Low	Very Low	Very Low
Co-incidence Consequence for exacerbating flooding	High	High	High
Cascade Likelihood	High	High	High
Cascade Physical Impact Permanence	Moderate Liquefaction	Moderate Liquefaction Vertical displacement	High Liquefaction Vertical displacement
Cascade Consequence for exacerbating flooding	High	Moderate	Moderate

8.5 Influence of Long-Term Climate Changes

8.5.1 Sea Level Rise

Sea level rise is not considered likely to directly impact upon the risk of earthquake hazard effects modifying flood hazard effects. However as the sea level rises then greater coastal inundation flooding can occur. The further into a future sea level rise scenario an earthquake occurs then if further land settlement occurs there will be a step change in the amount of inundation from coastal flooding as a result of the earthquake. The exact change in land surface elevation under a range of probability and source earthquakes is not known and this is what will control step changes in inundation at any point in time. The LDRP110 project considered a range of scenarios for future earthquake land surface changes to be included within planned hydraulic modelling. However, many scenarios either had limited data to allow predictions of land surface changes or appeared to result in changes that were too small to materially change modelled hydraulic outcomes.

8.5.2 Rising Groundwater levels

Groundwater levels in study catchments could rise as a result of rising sea levels. The groundwater levels changes are discussed in Section 9. Rising groundwater levels can impact upon the risks posed by future earthquakes. It is considered that liquefaction risk could increase if groundwater levels are higher and result in more saturated fine sediments near the land surface. This could result in greater volumes of ejected material, more changes to land surface elevations, increased lateral spread and increased transport of material into watercourses. These would therefore change the flood hazard risk. The exact impact of rising groundwater levels on earthquake related exacerbation of flooding risks is not known and therefore a gap.

8.5.3 Coastal Sediment Budget

It is not envisaged that the coastal sediment budget would change as a result of local source earthquake. Changes may however result from increased erosion of material and supply down larger rivers such as the Waimakariri River as a result of additional rainfall and storm events. This could result in increased coastal sediment supply. An Alpine Fault earthquake is considered likely to cause a major change in sediment supply down the Waimakariri, and coastal effects of this are unknown. However, ECan staff report they plan to manage such an effect on the lower reaches of the Waimakariri by increased sediment abstraction so that the stopbank flood management scheme is not compromised. How feasible such an approach is has not been considered. An increase in coastal sediments is unlikely to interact or influence the potential effects of any future earthquake on flood risk.

8.6 Key Earthquake Event Gaps Relevant to Flooding

Gaps in knowledge have focused on two areas, first the primary hazard i.e. do we know about the particular elements of an earthquake generated effect and secondly gaps in the interaction of the elements of the earthquake hazard with future flooding risk. A summary of the gaps is provided below (**Table 8-3**) for the ground shaking, vertical land displacement, liquefaction, local tsunami and hillslope instability elements.

Table 8-3 Gaps relevant to assessment of earthquakes and liquefaction

Gap Description	Benefit if Addressed / Risk if not Addressed	Indicative Budget Estimate and Timescale Required
Vertical land displacement in a range of probability and source future earthquake events. The LDRP110 study considered various approaches to modelling future earthquake land surface changes and decided to apply the CES again. This approach is proposed for this project but should be discussed as it does not allow for a range of information on different events. A key gap for LDRP97 is identifying the level of probability that causes geomorphological change that influences flood risk.	**Benefit**: If addressed a greater range of possible effects will be known for events that may be more probable than a repeat CES. **Risk**: If not addressed there could be challenge in terms of only using a low probability but high impact event.	Budget Estimate: Medium Requirement: For consideration of whether within the project
Knowledge of liquefaction risk from non-residential land At present gaps exist in the Technical Land Categories for all non-residential land hence liquefaction potential is not fully known. This should be addressed by existing LDRP work by T&T. This information should be reviewed further within this study when available.	Greater knowledge of liquefaction risk across the study area if addressed.	Budget estimate: Low Requirement: Within project
Interaction between liquefaction generation in a given future earthquake and the reduction that causes to drainage capacity of the network and channels. Work underway by T&T may tell us about liquefaction generation risk across all land areas/uses in the study area. However there is no means to then correlate actual liquefaction emissions within any given source/magnitude event and how this will fill drainage pipes and deposit within watercourses.	If addressed this will allow models to consider how the drainage network will perform immediately after quakes and the change in channel profiles that could occur. Risk if not addressed is that post future earthquake modelling would not consider this element of damage. However it could be assumed that this damage is short term as pipes would be cleared and liquefaction deposits dredged from waterbodies.	Budget estimate: Medium Requirement: Outside of project
Height and probability of local tsunami wave generation Information does not exist regarding the potential height of any tsunami generated by a local source earthquake. This information would be needed to then see whether it had potential to interact with flood, storm surge and tidal factors.	**Benefit:** If addressed is that the study will then know whether a local source tsunami would be big enough to cause flooding itself or exacerbate flooding impacts from rain events.	Budget estimate: High Requirement: Within Project
Land damage in vicinity of water courses and damage in drainage networks as a result of degrees of ground shaking	**Benefit** of addressing is to get detailed understanding of pots earthquake changes. Risk of not	Budget Estimate: Medium Requirement: Outside

Gap Description	Benefit if Addressed / Risk if not Addressed	Indicative Budget Estimate and Timescale Required
<u>in different source and magnitude events</u> Currently available data provides information on likely ground shaking magnitude but it is not considered practical to then translate this into sight specific damage and changes to drainage networks and channels in different source and magnitude future earthquake events that could be represented in a hydraulic model.	doing so is that post future earthquake modelling ignores certain effects.	project – the complexity of doing this is considered to be high and it may be better covered in the first consideration of future earthquake effects by leaving out or making simple assumptions.

8.7 References for Earthquake Hazards

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9. Groundwater Levels

9.1 Groundwater Interactions Relevant to Flood Events

Van Ballegooy (2013) summarise that, within Christchurch, the water table sits within the uppermost sediments (Christchurch Formation dune sand and Springston Formation gravels), and typically less than 10 m deep. Mapping of median groundwater table levels across the city (see Map 4: Depth to Groundwater Table) as measured between the Canterbury Earthquake Sequence and 2013 suggested that the water surface is generally more than 5 m below ground west of Christchurch City, but less than 2 m deep beneath much of the city (however, refer to Section 9.3 below). Broadly, the inland recharge zone gives way to a coastal discharge zone, with the transition occurring west of the city. Groundwater flow is in an overall northwest to southeast direction. Groundwater flow modelling suggests the aquifer system beneath Christchurch City has relatively active shallow flow, with recharge dominated by Waimakariri River infiltration. Resulting springs provide base flow of the Avon/Otakaro, Styx and Heathcote rivers included in the LDRP97 study.

The location of the groundwater table relative to ground levels determines soil saturation and areas where groundwater rises above the ground surface. These should affect antecedent conditions in surface flood models, as well as representation of permanently wet areas. A high groundwater table could occur during exceptionally wet periods (including as a result of extreme events and also with those associated with inter-decadal oscillations), seasonally during winter/spring or more permanently with climate change. Earthquake-induced subsidence of the ground would further bring the groundwater table closer to the ground surface, so that there is less unsaturated soil to absorb water during storm events (Hughes *et al*. 2015). Shallow groundwater is key in liquefaction hazards, with their cascading effects on land elevations, river channel capacities, and stormwater infrastructure such as stopbanks, drainage pipes and sumps, and the capacity of soakage features such as wetlands, swales and ponds. In the Heathcote catchment, increases in subsurface runoff are a particular hazard for the loess covered hill slopes as this can trigger slope instabilities. Groundwater level is also a critical part of the design capacity of soakage options.

The following interactions of groundwater and surface water could exacerbate flooding and are therefore relevant to this study:

- Colocation of groundwater and surface water flood hazards are likely in areas of low topography where water from any source can pond;
- Coincidence of groundwater and surface water flood hazards is likely, with flood-generating storms superimposed on seasonal wet conditions; and
- Cascade of high groundwater table exacerbating surface flooding is likely due to increases in soil saturation, and groundwater filling low topography, some of which is designated overland storage.

9.2 Influence of Long-Term Climate Changes

How groundwater levels may vary with climate change is, internationally, not well understood although focussed research is now being done (Taylor *et al.,* 2013) and subject of an LDRP investigation (LDRP45). There are two key interacting physical processes relevant to groundwater table variance in Christchurch:

1. **The effective recharge of varying rainfall patterns.** Typically, long duration extreme rainfall is understood as necessary for groundwater recharge, but some studies have revealed that high recharge can be experienced in some geologies from shorter duration more intense rainfall. Consequently, Green *et al.* (2011) reviewed a number of studies which have demonstrated both increases and decreases in recharge are possible with climate change. We did not find any of these studies with immediate applicability to the hydrogeology of Christchurch. The studies also highlighted that land use greatly influences recharge and, furthermore, Taylor *et al.* (2013) emphasises that indirect effects on groundwater through irrigation demand can be greater than the direct impacts of climate on recharge. However in Christchurch it may be more localised urban interactions (e.g. extraction for potable water) with groundwater which are more important.

2. **Sea level rise.** Rising sea level will raise the groundwater surface as it slopes down from the plains to the sea. In the Beca (2014) report for Dunedin City Council, it is suggested that the relationship between sea level and groundwater rise could be non-linear, such that every 0.1 m rise in sea level will result in a 0.19 m rise in the ground water table. This is based on the hypothesis that the present wastewater and stormwater networks are artificially depressing groundwater levels in a similar way to that occurring in Christchurch. However, the study actually uses a linear relationship. The relationship between groundwater surface and sea level rise is better understood and easier to project forward using theory and modelling, and is understood to be underway for Christchurch within the ongoing LDRP45 project. Sea level rise could also increase salinity for coastal groundwater aquifers with hydraulic connectivity with the ocean. It is recognised that this has consequences for water quality, which may indirectly impact on vegetation and potentially bank stability.

The literature emphasises that alongside climate-induced variations in groundwater level (and quality), anthropogenic changes will have a significant impact (e.g. abstraction for potable water or artificial drainage of groundwater). For example, land use will greatly influence recharge and Taylor *et al.* (2013) highlights studies which have predicted that impacts of abstraction from coastal aquifers is likely to dominate over sea level rise on changes in groundwater level and salinity.

9.3 Information and Data Sources

Van Ballegooy (2013) mapped median levels of the groundwater table across the city as measured between September 2010 and November 2013. Data was from 806 shallow monitoring wells across the city and it is important to recognise the limitations of:

- **Record length:** Groundwater levels in Canterbury fluctuate due to inter-annual and seasonal variations in rainfall and river recharge. The median groundwater surface developed by Van Ballegooy (2013) was typically based on 28 months of observations (although the period of record in many was 9 months or less) so is unlikely to have captured the full range of natural fluctuations;
- **Coverage of observations:** monitoring locations were concentrated within the city, with fewer observations available at the Sumner and Brooklands extents; and
- **Artificial suppression of groundwater levels:** As highlighted by Hughes *et al*. (2015), widespread drainage works have reduced groundwater levels under Christchurch over many decades, and installed waste water systems are long recognised as “leaky”, allowing infiltration into pipes with associated draining of groundwater and suppression of local water tables. This effect was highly exacerbated following breakage of pipes in the CES. Therefore, the available record of groundwater levels may underestimate the natural surface which will vary with climate change.

Median depths to groundwater are of interest for some applications but extremely high groundwater levels are most relevant to understand exacerbation of surface flooding. Therefore, future work should use 85th percentile high levels which is understood to be available for the same post-earthquake period.

9.4 Modelled Hazard Scenarios

LDRP45 is understood to be developing an updated baseline groundwater surface (85th percentile high levels) across the city. Based on this, projections of climate change on groundwater levels will be considered to predict future groundwater surfaces.

This future groundwater surface could be intersected with ground levels to predict any areas of groundwater breakout, and areas where high groundwater will increase soil saturation and reduce infiltration losses. This information could be used to vary loss parameters in the modelling which is not typically done in flood modelling to account for changes in the groundwater table. Groundwater and surface water interact across the study area, with the rivers supplying, or being supplied, by groundwater (GNS, 2013). As stated in Painter and Rutter (2015): where groundwater flooding is or could be contributing significantly to surface flooding, it needs to be accounted for in flood modelling. Such accounting appears to be rare or absent from current practice.

This is in line with Hughes *et al*. (2015), who called for urgent investigations addressing the dynamic geomorphic responses of urban rivers and coastal plains to relative sea-level rise, shoreline retreat, groundwater responses, liquefaction, subsidence, and coastal aquifer resources.

9.5 Key Groundwater Knowledge Gaps Relevant to Flooding

Table 9-1 summarises key gaps which could be filled either to progress this project (i.e. required within project – shaded green), or to progress future work connected with this project (i.e. required beyond project – shaded orange). Those required within this project are listed at the top of the table. Indicative budget estimates are classified according to: low <$20k, medium: $20 – $50k, high: > $50k.

Table 9-1 Gaps relevant to assessment of high groundwater levels

Gap Description	Benefit if Addressed / Risk if not Addressed	Indicative Budget Estimate and Timescale Required
Changes of extreme groundwater levels with sea level rise and rainfall changes Currently available data provides median depths to groundwater, whereas extremely high groundwater levels are of most interest to understand exacerbating flooding. In addition, the variation of extremely high groundwater levels, and of increased saline intrusion, with climate change is not currently known. Mapping should be updated following Council-commissioned study into impacts of earthquakes on groundwater, if new information is relevant (LDRP45).	**Benefit** is a more relevant understanding of the impacts of extreme groundwater levels on flood risk, as well as the variation of these impacts with climate change. **Risk** is that options considered do not appropriately consider and address groundwater change impacts.	Budget Estimate: Low Requirement: Within project
Accounting for future groundwater levels within climate change flood modelling Common practice for future flood modelling in Christchurch is to vary rainfall inputs and sea levels, alongside urban development. Varying antecedent / loss parameters and likely land use is not commonly done to account for projected raised groundwater levels. This is possible within the hydraulic models if suitable future scenarios can be developed.	The **benefit** of including this important component in future flood modelling is a more representative climate change scenario. The **risk** of not considering is that future flood predictions could be underestimated.	Budget Estimate: Low Requirement: Within project
Ongoing groundwater level measurement to refine groundwater surface maps Groundwater levels in recent decades are likely to have been artificially lowered by widespread drainage works recognized as “leaky” and breakage of pipes in the Canterbury Earthquake Sequence. Therefore, the generated surfaces and future projections of groundwater level change may underestimate the natural groundwater table. With ongoing observation of levels across the city, groundwater maps and projections should be periodically updated.	The **benefit** of ongoing measurement and future refinement of maps and projections is that any systematic underestimation of levels will be gradually eliminated and there will be greater certainty in the information. The **risk** of not doing this is underestimation of this significant hazard.	Budget Estimate: Medium Requirement: Beyond project
Changing groundwater salinity with sea level rise Sea level rise has the potential to increase salinity in coastal aquifers with hydraulic connectivity to the ocean. Increased salinity could result in vegetation die back and species migration, which in turn could impact on bank stability of coastal water bodies.	**Benefit**: Better understanding of ecology and drinking consequences **Risk** Lack of awareness of consequences	Budget Estimate: High Requirement: Beyond project

9.6 Groundwater Level References

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10. Regional Flood (Waimakariri River)

10.1 Overview of Regional Flood Physical Processes

Large scale flooding in Christchurch from the Waimakariri River bursting it banks and flowing through former overflow channels into the Avon and Styx Catchments has occurred on several occasions since European settlement of the city. This occurs due to the aggradation and avulsion processes occurring on the Waimakariri alluvial floodplain, on which Christchurch sits. Aggradation occurs when the slope of river bed decreases, resulting in deposition of the gravel sediments being transported by the river system, which in turn causes the river to switch course abruptly to create new channels or to re-occupy old relic channels it has not occupied for possibility decades, or even centuries (McSaveney & Whitehouse 1987). This sudden switching of channels occurs in flood events and is termed avulsion. As occurs in Christchurch, the existence of the old channels largely directs the course of future flooding if water enters them.

The normal response to these events is to construct stopbanks to contain the river in a fixed channel location on the alluvial plain. The location and size of the stopbanks are dependent the magnitude of the design flood and the width of channel required to pass this design flow. However, issues occur when flood levels exceed design levels, sometimes due raising of the river bed due to the deposition of gravel, or more commonly when changes in the river channel morphology results in high flow velocities and scour along sections of the bank resulting in breaching.

10.2 Christchurch Data and Modelling

The hydrology of the Waimakariri River has been re-visited on a number of occasions over the years as the length of record has increased and higher flows have been recorded. After much consideration, the flows adopted for the 100 and 500 year ARI flows in the Draft Waimakariri River Floodplain Management Strategy (Boyle 2017) are 4000 m^3/s and 5400 m^3/s respectively.

10.2.1 Historical Flooding and Protection

The earliest reported flooding was in 1859, followed by 1868 when much of north of the central city and land along the length of the Avon River was flooded. These floods led to the start of flood protection works on the river under the control of the South Waimakariri River Board with the construction of a series of groynes near Halkett to halt overflows into the Styx and Avon Rivers (Boyle 2017).

Following the passing of the Waimakariri Improvement Act in 1922, the Waimakariri River Trust was established to replace the River board, and charged with designing and constructing a comprehensive river training scheme in the lower reaches of the river from the mouth to the lower gorge. This scheme known as the “Hayes No.2 scheme” was launched in 1928 and provided the philosophy and methods for controlling the river for the next 60 years. The scheme design discharge was 4250 m^3/s, being the assumed maximum flow (Nelson 1928, quoted in Boyle 2017). In addition to the construction of extensive stopbank and groyne systems, the scheme included the excavation of Wrights Cut to bypass a tight loop in the river channel, closing the old South Branch at Crossbank, stabilising the river mouth, and a lower diversion channel between Stewarts Gully and Brooklands Lagoon (Boyle 2017). Prior to the scheme the mouth discharged to the sea at the south end of Brooklands Lagoon. In 1930, as part of the scheme, engineers made a cut in the sand hills to create a more direct course to the sea. However, the river continued to use the natural mouth until February 1940 when it shifted 3km north to its current position during a flood event (Boyle 2016). At this time the current Brooklands Spit area was a broad expansion of water and shifting sand bars with little vegetation, much different from the well developed and well vegetated of today. Rock bank protection on the north bank of the river at Kairaki opposite Brooklands Lagoon placed after this breach probably encourages the mouth to maintain its present position (Boyle 2016).

Reid & Dick (1960) noted that after initial success, the progressive gravel aggradation over time resulted in the system becoming less capable of containing major floods, with the February 1940 flood estimated at 3740 m^3/s, (Reinfelds 1995) breaking through the Crossbank and stopbank near Whites Bridge, and coming close to overtopping the stopbank at Halkett (Boyle 2017) The North Canterbury Catchment board (NCCB) having taken over responsibility of the protection works in 1946, were faced with further major floods in May 1950

(2570 m^3/s) and Dec 1957 (3990 m^3/s) resulting in numerous stopbank breaches and flooding. This latter flood, the largest on record, resulted water over 1.5m deep flowing through Kainga with the area from Englebrechts down to the Belfast Hotel and downstream nearly to Brooklands being described by the Christchurch Star newspaper as being “one vast lake” (Boyle et al 2015).

These floods demonstrated that the Hays No.2 Scheme no longer met its objectives mainly owning to the effects of gravel deposition in the river channel, resulting in the NCCB adopting of the Waimakariri River improvement Scheme in 1960. The immediate objective of this system was to pass without overflow a design flood of 4730 m^3/s (approximately 300 year ARI) with 1m of freeboard, and a longer term objective of to deal with the problem of aggradation in the lower reaches as far as practical and necessary (Boyle 2017). Work on the system started in 1963 and was completed in 1986, and could be considered a complete success for the safe conveyance of floodwater with major floods events in 1970 (2510m^3/s), 1979 (2910m3/s) and 1984 (2830m^3/s) being contained within the protection works (Boyle 2017). But, the downstream end of the gravel tongue had remained more or less stationary about the Stewarts Gully Sailing club since 1960 with no gravel having been passed to the sea as envisaged by the system. However, the commercial extraction rates from downstream of Crossbank approximately balanced the net influx, therefore reducing further aggradation.

Environment Canterbury (ECan), who superseded the NCCB in 1989, prepared a proposed Waimakariri Floodplain Management Plain in 1990, which included non-structural flood protection measures as well as structural measures. The aim of the plan was to minimise potential damage to Christchurch City, Kaiapoi and Selwyn District communities for a 30 year period and beyond (Boyle 2017). Based on physical, economic, social and environmental criteria a preferred protection option was selected involving 18 protection measures covering river control, land-use management, community preparedness, emergency actions and Civil Defence. However, in 1996 ECan withdraw the proposed Plan due to lack of support from Christchurch City & Waimakariri District Councils to prosed rules controlling land-use for building purposes and public perception that the measures were too restrictive. Following withdrawn of the Plan, ECan instructed staff to proceed with implementing the structural works of the Proposed Plan via the council’s Annual Plan process, with the land-use controls to be pursued through the City and District Council planning processes.

10.2.2 Current Waimakariri Flood Protection Project

The implementation of the above structural package of work is referred to as the Waimakariri Flood Protection Project (WFPP), which has the objective of adding strength and resilience to the existing flood protection system and to significantly lower the risk of break –outs during flood events by the construction of a secondary stopbank system along with upgrades primary banks – primarily downstream of SH1. Location of the secondary banks involved consideration of most likely failure zones to the primary banks, and that the outflows from these would occupy the former floodplain channels identified on geomorphic maps. Three break-out zones were identified on the south bank being:

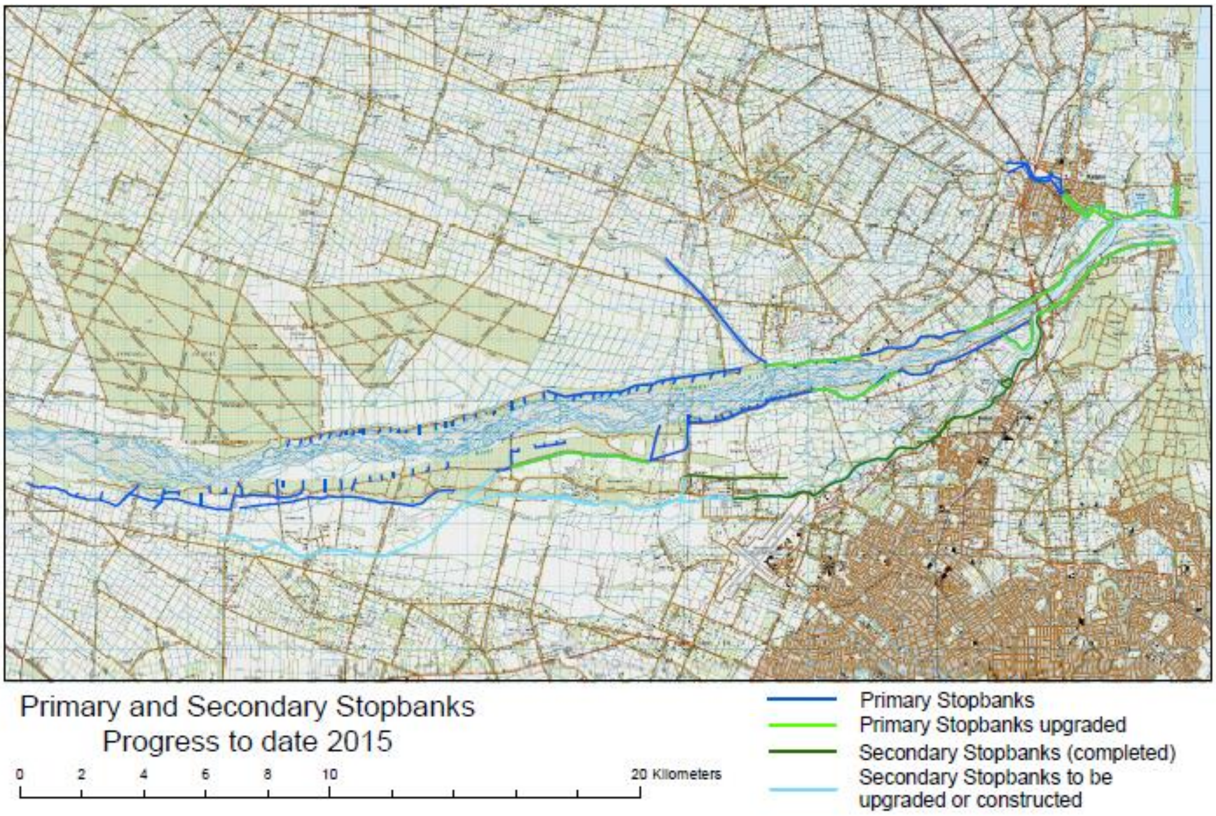
- Halkett Zone: Courtenay to West Melton – the zone from which floodwater inundated Christchurch in 1868
- McLeans Zone from West Melton to Crossbank – the zone from which breakout water would get into the Avon Catchment.
- Crossbank zone to the sea – the zone for which breakout water would get into the Styx Catchment.

Construction of the secondary banks started in 2009 with a proposed completion date of 2019 (Boyle 2017). At present (2017) two sections of the bank which are still to be completed are those upstream of the Halkett Zone. A map of location of works undertaken and planned under the WFPP is presented in Figure 10-1.

The design capacity of the WFFP is that the primary banks can contain a flow of 4730 m^3/s at Crossbank, and 5100 m^3/s upstream of that. However, recent hydraulic investigations indicate that this primary bank system may be able to contain a 500 year ARI flow of 5400 m^3/s (Tony Boyle, pers com). The design intent of the secondary bank system up stream of SH1 is to totally protect Christchurch from a flow up to 6500 m^3/s, but ECan are wary of putting an ARI on this size flow due to the large error bands ((Tony Boyle, pers com).

Downstream of SH1, where the overflow has been returned to the river by the secondary banks, the primary banks are designed to pass the 5500 m^3/s flood with a 0.5m freeboard.

Figure 10-1 Waimakariri River Flood Protection Plan Progress 2017. (Map supplied by A.J. Boyle ECan).



10.3 Process Interactions Relevant to Local River Flood Hazards

Due to different weather systems being responsible for flooding in the Waimakariri Catchment from those responsible for flooding in local Christchurch catchments, the likelihood of temporal co-incidence between regional and local flooding is considered to be low. However, it is possible that that strong north-west conditions promoting flooding in the Waimakariri can be followed by southerly fronts resulting in high magnitude flooding in Christchurch catchments, so cascades over very time frames are possible.

10.3.1 Stopbank Contained Events

Interactions between Waimakariri River flood events contained within the primary stopbanks and local FPF events in Christchurch are limited to potential flooding in Brooklands Lagoon. Flooding further upstream in the Styx catchment is prevented by the Styx tidal gates, first installed in 1934 and replaced in 1981.

Within Brooklands the potential effects include:

- Direct inundation from increased water levels.
- Mouth instability and southward migration from erosion of the tip of Brooklands Spit, or in the most extreme case breaching the spit to establish a new mouth back in a southern lagoon as prior to 1940 which would subject the lagoon to greater river flooding.
- Increase in the tidal prism of the mouth with bed scour of the inlet channel due to extreme flow velocities. The result of this would be increases in the tidal flows into the Lagoon which may alter flood levels and sediment transport in the lower river reaches.

However, from discussions with ECan Rivers Engineer, Tony Boyle, the experience with large flood flows is that high river levels do not greatly alter the pre-existing tidal levels in the Lagoon due to scour of the sandy lower river bed. Hence lagoon flood levels are almost totally set by tide levels, and therefore only become an issue when combined with extreme tide events.

For the potential threat of southward mouth migration, this has not been recorded to occur in any Waimakariri flood since the current mouth position was established in 1940. The mouth did migrate southwards at rates of around 20m/yr in 2011/12, prompting ECan to undertake an investigation to determine the effect that migration by 1.5km and 3km (e.g. back to former mouth position) would have on flooding within the lower Waimakariri River. The conclusion from the investigation was that since such a migration would also result in a very wide opening to the sea, minimal additional engineering works would be necessary in the lower Waimakariri channel to deal with increase flood levels, and that the rate of mouth migration was such that it would take a significantly long time before this was needed. The recommendation of the study was therefore to allow nature in relation to migration to take its course in the short to medium term (Boyle 2016). A follow-up study in 2016 found that the mouth position had ceasing migrating south between 2013 and 2016, therefore also recommended that no intervention for mouth stability was required.

10.3.2 Stopbank Failure Events

A large Waimakariri River flood that breached both the primary and secondary stopbanks could have the following additional interactions with local Christchurch FPF events, particularly in the Styx and Avon catchments.

- Direct inundation from Waimakariri break-out water travelling down old floodplain channel within the city and discharging into the Styx and Avon River channels
- Potential drainage system infrastructure failure and reduced capacity due to overland flows from Waimakariri break outs. This could include the potential impacts of urban debris carried by this flood water.

However, following the completion of the WFPP in 2019, it is assumed by ECan that the risk of such a breach event of the secondary banks has such a low probability that it not worth considering further in the context of multi-hazards for Christchurch FPF events.

Other potential Waimakariri stopbank failure mechanisms considered in the context of multi-hazards are the effect of earthquakes on stopbank stability, and the effect of raised river bed levels and channel morphology with gravel accumulation on the scheme capacity. For earthquake effects, during the CES the stopbanks below SH1 slumped in both the Sept 2010 and Feb 2011 events due to ground failure in soft sediments. The banks were reconstructed both times with better foundations where required, so are considered to be at a better standard to withstand similar local and regional earthquake events but still expected to fail in a distant Alpine Fault event (Boyle *pers com*). However, even with similar failures in future earthquakes, the banks will still be able to contain a flood in the order of 3300 m^3/s (Boyle *pers com*).

For gravel accumulation raising bed levels, the current practice of removing the accumulation is to be continued under the Waimakariri River Floodplain Strategy, where it is noted that this is a very important initiative and is working well (Boyle 2017). It is anticipated that potential large scale sedimentation in the lower river as a result of a distant Alpine Fault would be handled in the same way (Boyle *pers com*).

10.3.3 Co-location and Cascade summary

Based on the above discussion, and the level of protection to be provided once the WFPP is completed, the anticipated likelihood of co-incidence and cascades, and their consequences for exacerbating flooding are presented in **Table 5-41**.

Table 10-1 Summary of Anticipated Co-incidence and Cascade impacts for Waimakariri River Flood and Christchurch FPF Events

Interaction with FPF Events	Flood contained in Stopbank	Flood breach of 2nd stopbanks
Co-incidence Likelihood	**Low**	**Very Low**
Co-incidence Consequence for exacerbating flooding	**Moderate** mouth migration	**High**
Cascade Likelihood	**Moderate**	**Low**
Cascade Physical Impact Permanence	**Moderate** mouth migration	**Moderate**
Cascade Consequence for exacerbating flooding	**Moderate** mouth migration	**Moderate**

10.4 Influence of Long-Term Climate Changes

The potential effects of long-term climate changes on Waimakariri flooding are mainly related to changes in the flood frequency and magnitude due to changes in weather systems, and sea level rise affecting the tail water conditions for flood discharge to the sea.

For the first of these, information on future projections a rainfall and storms is presented in section 4.3 of this report. For sea level rise, the likely effects on coastal-fluvial interactions are as presented in section 6.2. An additional effect for sea level rise is on the ability of the lower river stopbanks to absorb the predicted rise without compromising the protection capacity. ECan River Engineer Tony Boyle considers that the existing stopbank elevations of 4m above MSL, which is 2.3m above Lyttelton 200 year ARI storm tide, is sufficient to accommodate sea level rise over the next 100 years.

10.5 Key Regional Flood Event Gaps Relevant to Local River Flooding

Table 6-3 summarises key gaps which are considered to be required to be filled to progress this project (shaded green), or other which are or interest for the wider understanding of Christchurch hazards, but are considered to not be vital for the progress of this project (shaded orange). Those required within this project are listed at the top of the table. Indicative budget estimates are classified according to: low <$20k, medium: $20 – $50k, high: > $50k.

Table 10-1 Gaps relevant to assessment of Regional flood hazards

Gap Description	Benefit if Addressed / Risk if not Addressed	Indicative Budget Estimate and Timescale Required
Probability of a short cascade flood event The probability of two weather systems causing flooding from the Waimakariri followed by local rivers is unknown.	Benefit: Likelihood of risk under multihazard approach is identified. Risk: Short cascade event not addressed in Stage 3.	Medium Required within project
Understanding of river mouth dynamics, Brooklands Spit stability and breaching potential in large Waimakariri flood	**Benefit**: Improve understanding of the probability of mouth migration	Medium - High

Gap Description	Benefit if Addressed / Risk if not Addressed	Indicative Budget Estimate and Timescale Required
events At present, no in depth investigation of these parameters have been undertaken	and the effect this would no flooding in and around Brooklands Lagoon.	

10.6 References for Regional Flooding

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11. Hill Slope Instability Events (Co-seismic and Aseismic)

11.1 Overview of Hillslope Instabilities Physical Processes

Hill slope erosion hazards comprise the downslope movement of materials under the influence of gravity (Gill & Malamud, 2014), including in the study area rockfalls, slip/sheet and slope erosion, ‘soil erosion’ from tunnel gullying, plus rockfall and landslides associated with earthquakes. ‘Causes’ and ‘triggers’ refers to factors which make a slope susceptible to slope instabilities versus events which initiate the final failure (Smith &Petley, 2009).

Causes include weathering; increase in slope angle; removal of lateral support (often as a result of river erosion at its base); head loading (when additional weight is placed on a slope); changes in the water table; and removal of vegetation. Key triggers are loss of shear resistance as a result of increased moisture, usually as a result of intense or persistent rainfall; earthquake shaking and human activity (such as quarrying or slope cutting in road construction) (Smith & Petley, 2009).

A type of erosion common in the Port Hills is tunnel gullying, where water migrates down through loess sediment until it reaches a less permeable layer, concentrating to form and underground water channel. The progressive widening of such features eventually leads to their collapse (Basher, 2013). Since this type of mass movement is triggered by groundwater flows, events are not necessarily coincident with extreme rainfall events (Lynn, 2017). Tunnel gullying can cause a secondary flooding hazard by sedimentation of water courses, a phenomenon observed in the Port Hills catchments (Hicks, 1993; Perez, 2012).

Slope instabilities in the form of rockfalls and debris flows occurred on the Port Hills during the Canterbury Earthquake Sequence (CES), resulting in building damage, fatalities and evacuations. These have been extensively mapped and analysed (e.g. Khajavi et al., 2012; Massey et al., 2013; Heron et al., 2014; LINZ, 2015), highlighting areas prone to rockfall and at risk of cliff collapse. Evidence was also found of earthquake-triggered tunnel gully collapse in all Port Hills valleys (Stephen-Brownie, 2012).

Follow-on effects of the CES historical slope instabilities are likely to occur in future. For example, ground damage associated with the CES has increased the risk of landslides in the Port Hills. Future trigger events such as another earthquake or excessive rainfall may cause landslides to affect tributaries in the Port Hills sub-catchments areas. With rockfalls and slip/sheet slope instabilities being known hazards for parts of the Port Hills, there is also the possibility of an earth/ rock dam and subsequent upstream ponding.

11.2 Process Interactions Relevant to Flood Events

In terms of influences on flood hazard, hillslope erosion multi-hazard interactions primarily concern (a) the potential direct impacts of hillslope erosion events on drainage infrastructure, and (b) the rates and volumes of sediment released into natural and built components of the drainage system in the southern part of the project study area.

Multi-hazard analysis is crucial in the context of hillslope erosion plus flood hazards, with primary, secondary and even tertiary hazard interactions possible. For example, earthquakes or severe storms can trigger rockfall or induce tunnel gullying, leading to landslides blocking a river or excess sediment loads washing into drainage and flood management infrastructure, thereby creating or exacerbating flooding and/ or impacting stormwater system functionality.

The most significant interactions between hillslope erosion and flood hazards are likely to operate at event scales (e.g. sudden mass movements or hillslope failures before or during significant rainfall events), while less important interactions will occur over long time scales (e.g. runoff induced erosion such as tunnel gullying). Coincidence of the former, more significant hillslope erosion events are likely to be constrained in terms of their timescales of interaction with flood hazards, although a statistical analysis of the correlation between extreme rainfall events triggering mass movement versus fluvial and/or pluvial flooding represents a research gap. In terms of the latter and as noted earlier, tunnel gullying is triggered by groundwater flows such that events are not necessarily coincident with extreme rainfall events

11.3 Influence of Long-Term Climate Changes

A research gap exists regarding the correlation of extreme rainfall events triggering mass movement and the coincidence of fluvial and/or pluvial flooding during such weather. That is, we have no analysis of the likelihood of certain types of extreme synoptic conditions triggering mass movement, nor if any such weather patterns are those that also cause flooding in Christchurch. Since rain storm intensity is predicted to increase with climate change, then any future predicted changes in the relationships between weather, hill slope erosion and flooding also represent a research gap.

11.4 Information and Data Sources

Data on hillslope erosion hazards in the study area comprises three main types:

- Data on recorded historical erosion events[4];
- Data on areas assessed as being currently prone to erosion processes[5]; and
- Predictions of areas currently prone to tunnel gullying.

These three data types have been mapped in Map A9 (**Appendix A**). It is worth noting that significant anomalies exist between the historical records and predicted risk areas, highlighting data limitations. For example, large scale slip sheet mass movements have historically been recorded across confined areas of the Port Hills, but are possible across most of these hillslopes, and are potentially more likely in the future than predictions suggest due to the recent fires and since there has been no little recent erosion in some susceptible areas.

Previous assessments have also been biased towards examining risk in areas with residential and/or key infrastructure, meaning that risks may be underestimated for less developed areas. This is a data limitation of concern in this project since we are interested in the potential direct impacts of hillslope erosion events on drainage infrastructure as well as the rates and volumes of sediment released into natural and built components of the drainage system. Given these spatial and accuracy limitations, it is unlikely that data of sufficient quality and quantity exist for a robust probability analysis of this hazard.

11.5 Key Hill Slope Event Gaps Relevant to Flooding

Table 11-1 summarises key gaps which could be filled to progress future work connected with this project (i.e. required beyond project – shaded orange). Indicative budget estimates are classified according to: low <$20k, medium: $20 – $50k, high: > $50k.

Table 11-1 Gaps relevant to assessment of hillslope erosion

Gap Description	Benefit if Addressed / Risk if not Addressed	Indicative Budget Estimate and Timescale Required
Full Port Hills erosion risk data coverage Christchurch hillslope erosion data availability is limited, with current coverage biased towards residential areas and large data gaps across undeveloped hillslopes. Thus the risk of mass movement events leading to the blocking of drainage infrastructure and the sediment load that this infrastructure needs to be designed to cope with are potentially underestimated.	**Benefit**: Identify drains etc. that could get blocked from erosion. **Risk**: Don't have full understanding.	Budget Estimate: Medium Requirement: Outside project
Weather trigger and flood coincidence analysis A research gap exists regarding the correlation of extreme rainfall	**Benefit**: Identify key risk areas. **Risk**: Don't identify key risk areas	Budget Estimate: Medium Requirement: Outside project

[4] available from the CCC Web Feature Service, WFS
[5] available from the CCC Web Feature Service, WFS

Gap Description	Benefit if Addressed / Risk if not Addressed	Indicative Budget Estimate and Timescale Required
events triggering mass movement and coincidence of fluvial and/or pluvial flooding during such weather. (e.g there appears to be little analysis of the likelihood of certain types of extreme synoptic events triggering mass movement, nor if any such weather patterns are those that also cause flooding in Christchurch). Since rain storm intensity is predicted to increase with climate change, then any future predicted changes in the relationships between weather, hill slope erosion and flooding also represent a research gap.	and rainfall event causes slip.	

11.6 Hill Slope Instability References

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PART 2: MULTIPLE HAZARD SPATIAL CO-LOCATION GAP ANALYSIS

12. Spatial Co-Location of Multiple Hazards

The spatial co-location of multiple hazards is the first step in the identification of multi-hazards. It determines where multi-hazard interactions are going to occur, so where we need to focus our attention on the impacts of multi hazards.

12.1 Methodology

12.1.1 Mapping

For this study, the methodology involved gridding the study area into regular 1km x 1km grid cells as shown in Appendix B map B1, then undertaking the following two pass assessment of the co-existence based on available hazard information:

1. First pass assessment of number of different individual hazards experienced within each grid cell. The maximum number of hazards within any one grid is eight, including flooding. The heat map for this first pass assessment is presented in Appendix B map B2.

2. Second pass assessment where the intensity of the hazards is taking into account in the spatial co-location mapping, to give more detail on the likely severity of the co-location. For this assessment, an intensify scale of 1-3 was applied to each hazard, with a score of 3 for a high intensity hazard and 1 for a low intensity hazard. Due to the binary nature of the data for some hazards, the intensify scale for these is limited to scores of 3 (high intensity) and 2 (medium intensity), while Port Hills Slope Instability hazards were excluded from the analysis due to the lack of co-location with other hazards. The resulting maximum combined intensity score was 21 (e.g. all 7 hazards have high intensity). The classifications used to define the intensity scales were adapted for local data availability from that used by Hart and Hawke (2016) in assessing multi hazards in the Heathcote Catchment. The resulting classifications used in this study are presented in **Table 12-1** and discussed in more detail below.

   The heat map for this second pass assessment is presented in Appendix B, map B3. For interpretation purposes the combined intensity scores were grouped into the following categories:

   - Extreme intensity hazard co-location: Sum of Intensity scores greater than 18.
   - High intensity hazard co-location: Sum of Intensity scores between 15 and 18.
   - Moderate intensity hazard co-location: Sum of Intensity scores between 10 and 14.
   - Low intensity hazard co-location: Sum of Intensity scores less than 10.

12.1.2 Hazard Intensity Classification Matrix

The hazard intensity classification used Hart and Hawke (2016) was based on those used in a European study for assessing regional scale hazard intensities (Kappes *et al* 2012, Menoni 2006). However, for the data available for the current study area, some of the classification ranges were not available (e.g. coastal inundation depth), or not applicable due to the cell size used (e.g. coastal erosion). Therefore, in order to make the classification scales more relevant to the local data the scales presented in Table 12-1 were applied to co-location second pass assessment. The Table also includes notes to justify the variation in scales from these presented in Hart and Hawke (2016).

Table 12-1 Hazard Intensity classification applied to co-location second past assessment

	Mapped Parameters for each Intensity Scale			
Hazard	**High Intensity (score=3)**	**Medium Intensity (score=2)**	**Low intensity (score=1)**	**Notes on changes to scales from Hart & Hawke (2016)**
Flooding	Flood management Areas	High Flood Hazard Management Area	Nil	Flood depths not available in data layers used
Coastal Erosion	2065 area	2115 area	Nil	% of erosion surface compared to stable surface not appropriate at cell size
Coastal Inundation	2065 area	2115 area	Nil	Inundation depths not available in data layers used
Tsunami (1)	>1m Depth	0.6-1m depth	0.1-0.5m depth	Adjusted to fit depth layers in data provided
Vertical Displacement	>±0.5m	>±0.1m to ±0.5m	≤±0.1m	Adjusted for range of displacement in CES
Liquefaction	Red Zone	LTC3 land	LTC2 land	% of liquefaction surface compared to stable surface not appropriate
Depth to Groundwater	<1m	1m – 3m	>3m to 5m	No change
Note:	(1) Tsunami is just distant source event as is largest hazard of the tsunami events (2) Vertical displacement and Liquefaction taken from local CES events, rather than regional and distant earthquake events.			

12.2 Limitations

The co-location analysis uses the best data available at the time, but is limited by the following limitations

- Data Gaps: There are gaps in the spatial data for liquefaction, and in the modelled data for vertical displacement (not full CES) and tsunami (not account for river water levels). The tsunami data is also limited to just the regional tsunami as the more spatially severe distant tsunami data was not available from ECan at the time of the analysis.

- Different frequencies of hazard: The co-location takes no account of the different frequencies of the hazard events for which geospatial data is available. For example low frequency events such as tsunami with mapped ARI's of 1;2500 years are afforded the same likelihood of occurrence as relatively high frequency hazard events such as flooding (ARI's 200-500 year). Similarly, current hazardous conditions such as high groundwater levels are considered alongside future changes over 100 years in coastal erosion and coastal inundation.

- Inconsistency in hazard intensities: A range of hazard intensities are used in the second pass assessment, and are assigned a classification of high, moderate and low. However, there has been no sensitivity analysis on how significant or consistent these intensities are with regards to their potential to exacerbate FPF effects. This is considered a major limitation of the second pass assessment methodology, which requires further refinement.

- Thresholds of combined multi-hazard intensity levels: These were arbitrarily set, which may not accurately reflect the intensity of the multi-hazard risk. Sensitive testing and review of the thresholds should be carried out once the data gaps have been addressed.

- Comparison of analysis results of hazard frequency and intensity by area within each catchment potentially being skewed by the arbitrarily set catchment boundaries.

It should be noted that this analysis is just for the spatial co-location of hazards, not for the temporal co-incidence or potential for changing FPF trigger levels from cascading effects.

12.3 Analysis

12.3.1 First pass assessment

Occurrence of Hazards within Cells

This analysis involved counting the number of hazards that were mapped as being able to occur within each 1km x 1km cell, regardless of the area of the cell covered by the hazard. The results of the analysis for each of the 4 catchments within the study area, plus the Residential Red Zone are presented in **Table 12-2** and **Figure 12-1.**

Table 12-2 Results of Co-location of Hazards by Cell numbers.

Number and percentage of cells with different Levels of Hazard Co-location								
Catchment	**Total No of Cells**	**Cells with 1 or more hazard**	**Cells with 2 or more hazards**	**Cells with 3 or more hazards**	**Cells with 4 or more hazards**	**Cells with 5 or more hazards**	**Cells with 6 or more hazards**	**Cells with 7 or more hazards**
Styx – Brooklands	45	45 (100%)	45 (100%)	44 (98%)	40 (89%)	29 (64%)	22 (49%)	2 (4%)
Lower Avon	49	49 (100%)	49 (100%)	46 (94%)	43 (88%)	33 (67%)	24 (49%)	9 (18%)
Southshore-Estuary (1)	26	26 (100%)	26 (100%)	23 (88%)	20 (77%)	18 (69%)	14 (54%)	13 (50%)
Lower Heathcote	30	30 (100%)	30 (100%)	30 (98%)	28 (93%)	24 (80%)	16 (53%)	9 (30%)
TOTAL	**150**	**150 (100%)**	**150 (100%)**	**143 (95%)**	**131 (87%)**	**104 (69%)**	**76 (51%)**	**33 (22%)**
Residential Red Zone	**30**	**30 (100%)**	**30 (100%)**	**30 (100%)**	**30 (100%)**	**30 (100%)**	**27 (90%)**	**11 (37%)**
Note:	(1) Includes Sumner							

The key points from this multiple hazard analysis are as follows:

- At least two hazards are co-located across all 150 cells, with close to 90% of cells in the Styx-Brooklands, Lower Avon and Lower Heathcote catchments being exposed to four or more different hazards.

- Close to 50% of cells across all four catchments are exposed to six of more different hazards. From Map B2, it can be seen that as anticipated the majority of these the cells with high hazard co-location are adjacent to the river channels, estuary, Brooklands Lagoon, and the coastal sand spits at Southshore and Brooklands. There is a strong co-relation with the Residential Red Zone with additional high co-location cells at Ferrymead-Woolston, Horeshore Lagoon, South Brighton, and Lower Styx Rd-Spencerville Rd areas.

- 50% of cells in the Southshore-Estuary catchment and 30% in the lower Heathcote catchment are exposed to all seven hazard types. Conversely with the Styx-Brooklands catchment, only 2% of the cells are exposed to the maximum number of hazards included in the analysis.

- While the distribution of hazards co-location across the four catchments is similar, generally speaking the least hazardous catchment in terms of co-location occurrence is Styx-Brooklands (excluding the RRZ area).

- There is an extremely high co-location of hazards within the Residential Red Zone, with all 30 cells being exposed to five of more hazards (c.f Study area average 69%), and 90% of cells are exposed to 6 of more hazards (c.f Study area average 51%).

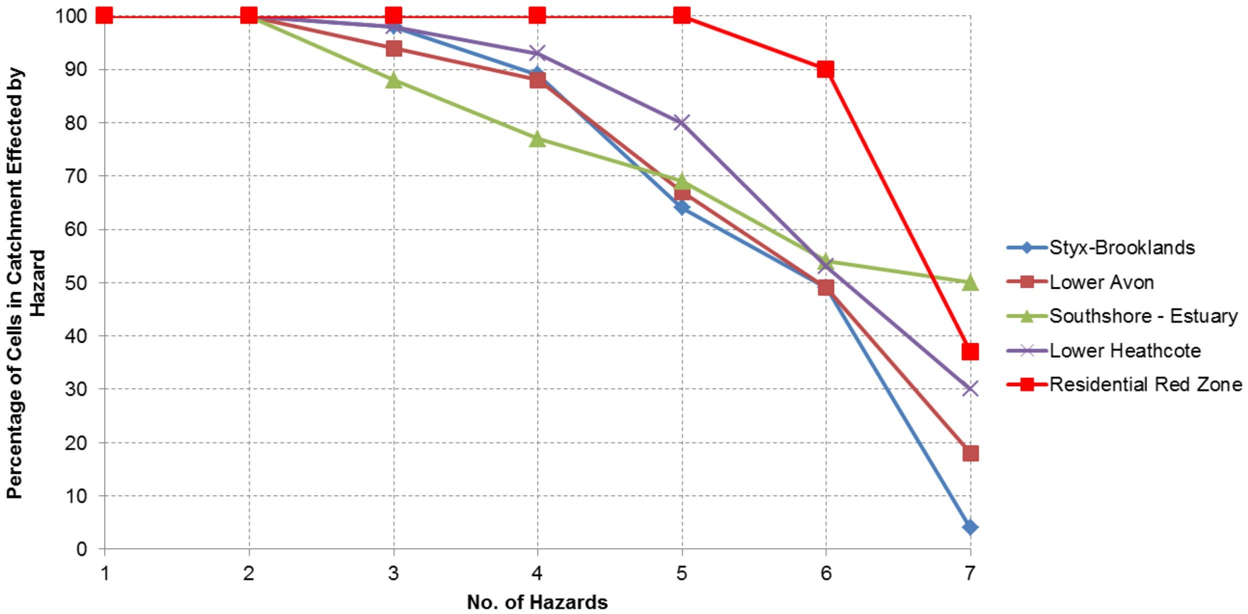


Figure 12-1 Comparison of multiple hazard co-location by catchment and the Residential Red Zone

While this analysis is useful for defining broad co-location patterns, it does not provide any information of the size of area affected by the different levels of hazard co-location. This limitation is addressed in the following analysis.

Co-location of Hazards By Area

GIS analysis was used determine the area within each grid cell exposed to the different levels of hazards co-location. The results of this analysis are presented in **Table 12-3** and **Figure 12-2**.

The key points of this analysis include:

- Only 20% of the total study area is not exposed to any of the mapped hazards. The catchment with the largest percentage of non-hazardous land is Styx-Brooklands with 28% not exposed to any hazards. However, as pointed out in the methodology limitations, this could be due to inconsistencies between catchments with the study area boundaries (e.g. Styx-Brooklands including a larger percentage of land located a fixed distance from the river or coast).

- 45% of study area is exposed to one or two co-located hazards. The Southshore – Estuary catchment has the greatest percentage in this modal range, with 65% of the catchment area.
- Over 20% of the study area (over 3000 hectares) is exposed to moderate or high multiple hazard co-location, being exposed to four or more hazards. The lower Avon catchment has the largest percentage of area in these classes with 24% of the catchment area (over 1000 hectares).
- Only 3.6% of the study area is exposed to high multiple hazard co-location, being exposed to six or more hazards. The lower Avon catchment has the largest percentage of area in these classes with 6% of the catchment area (approx. 270 hectares).
- In contrast to the individual catchments the majority of the Residential Red Zone is strongly exposed to multiple hazards, with 86% of the area (approximately 455 hectares) being exposed to 4 or more hazards, and 24% (approximately 126 hectares) being exposed to 6 or more hazards.

Table 12-3 Results of Multiple Hazard Co-location by Area

Area Exposed to different Levels of Hazard Co-location									
Catchment	**Total Area (hectares)**	**Nil hazards**	**One hazard**	**Two hazards**	**Three hazards**	**Four hazards**	**Five Hazards**	**Six Hazards**	**Seven Hazards**
Styx – Brooklands	3871.57	1165.41 (30.1%)	868.57 (22.4%)	528.91 (13.7%)	343.14 (8.9%)	459.66 (11.9%)	441.60 (11.4%)	63.29 (1.6%)	0.99 (0.0%)
Lower Avon	4450.77	861.64 (19.4%)	1201.24 (27.0%)	878.43 (19.7%)	426.55 (9.6%)	375.00 (8.4%)	436.69 (9.8%)	262.04 (5.9%)	8.21 (0.20%)
Southshore-Estuary (1)	1539.76	193.21 (12.5%)	569.22 (37%)	467.92 (30.4%)	79.10 (5.1%)	122.16 (7.9%)	80.15 (5.2%)	25.12 (1.6%)	2.88 (0.20%)
Lower Heathcote	2886.12	586.33 (20.3%)	821.69 (28.5%)	519.38 (18.0%)	346.98 (12.0%)	291.92 (10.1%)	216.78 (7.5%)	88.14 (3.1%)	14.36 (0.5%)
TOTAL	**13036.52**	**2806.59 (21.5%)**	**3460.71 (26.5%)**	**2394.63 (18.4%)**	**1195.77 (9.2%)**	**1248.73 (9.6%)**	**1175.22 (9.0%)**	**438.59 (3.4%)**	**25.75 (0.2%)**
Residential Red Zone	**530.07**	**0.41 (0.1%)**	**13.22 (2.5%)**	**17.93 (3.4%)**	**42.96 (8.1%)**	**119.80 (22.6%)**	**209.13 (39.5%)**	**123.25 (23.3%)**	**3.08 (0.6%)**
Note:	(1) Includes Sumner								

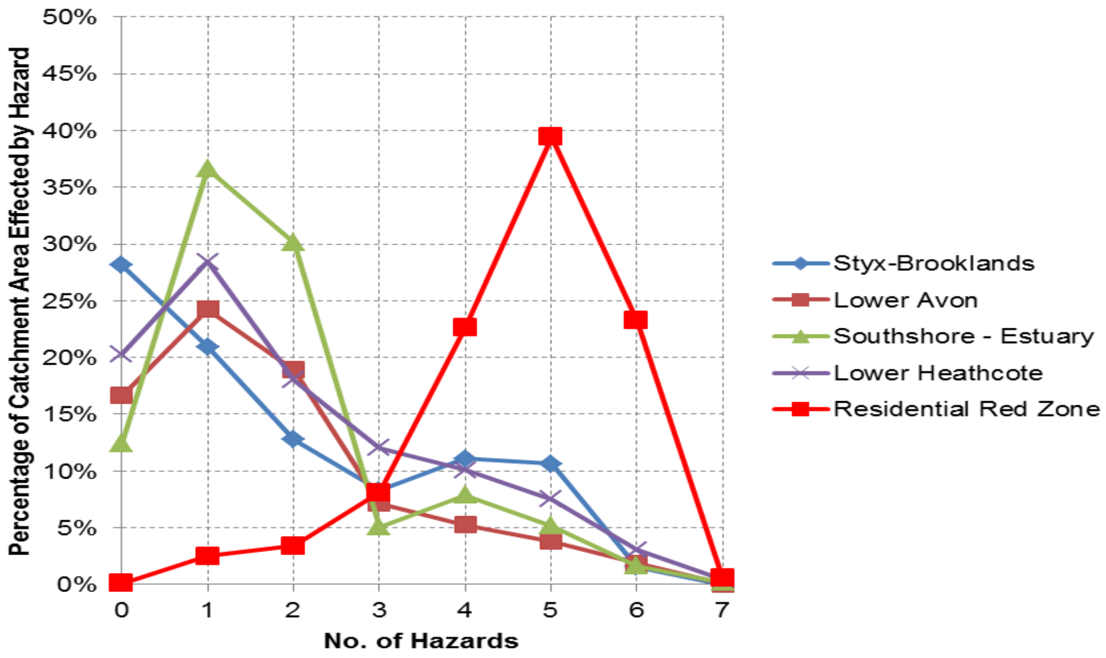


Figure 12-2 Comparison of area affected by multiple hazard co-location

12.3.2 Second pass assessment; intensities of hazard

The purpose of this assessment was to combine the intensities for each hazard given in Table 12-1 to provide more detail of the likely severity of the hazards that are spatially co-located. The resulting spatial distribution of co-location intensity is presented in Map B3 (Appendix B), which visually displays the following general patterns:

- The majority of the study area has combined low intensity multi-hazards
- The co-location of combined medium and high intensity multi-hazards is concentrated around the margins of the three rivers (Avon, Heathcote, Styx), the Avon-Heathcote estuary, Brooklands Lagoon, and Sumner.
- The co-location of combined extreme intensity multi-hazards is strongly concentrated in the Residential Red Zone areas.

GIS analysis of the data presented in **figure 12-3** supports these patterns with the following findings:

- 76% of the total study area (≈ 9560 ha) has combined low intensity multi-hazards. There is a similar percentage across all four catchment areas.
- Conversely, only 3% of the total study area (≈ 360 ha) is subject to combined high intensity multi-hazards, and only 0.01% (≈ 1 ha) is subject to combined extreme intensity multi-hazards. The low percentage for the combined extreme intensity multi-hazards confirms the earlier suggestion that the intensity levels may not be right and should be reviewed once the data gaps have been filled.
- All of the area subject to combined extreme intensity multi-hazards, and is 90% of the combined high intensity hazard area, is located within the Residential Red Zone, Conversely only 14% of the combined low intensity multi-hazard area is within the Residential Red Zone.

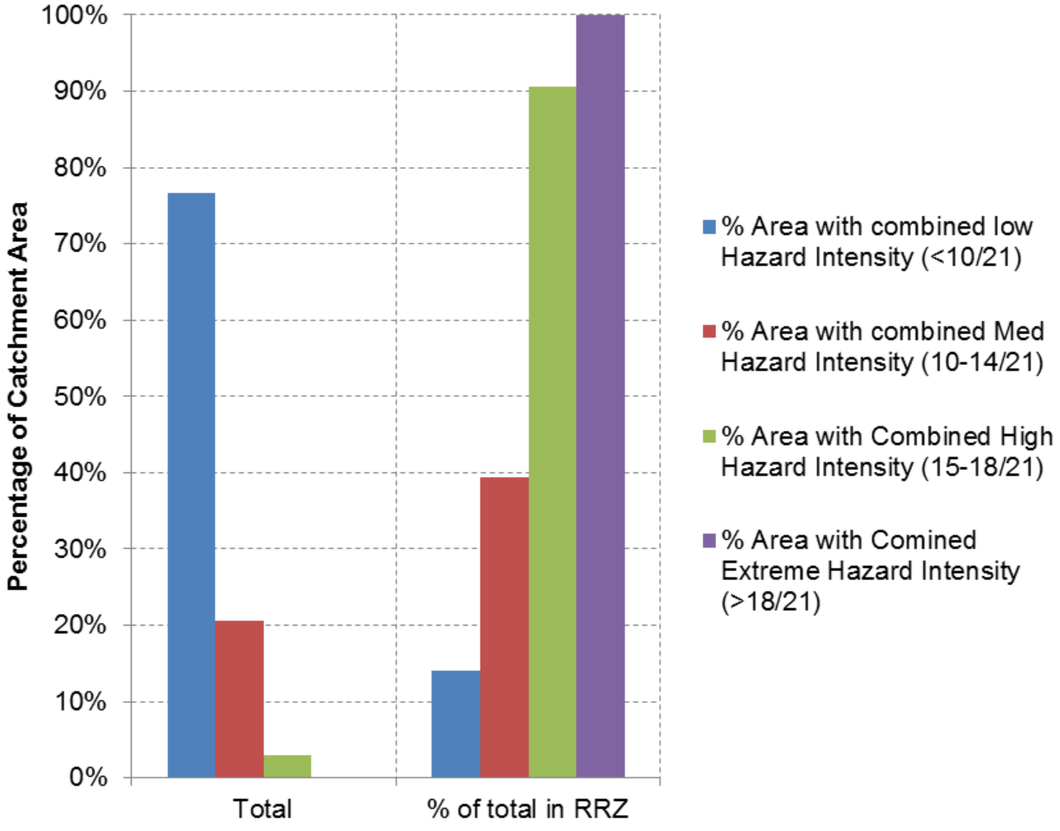


Figure 12-3 Comparison of area affected by different intensities of combined multiple hazard co-location.

12.3.3 Conclusions

Most areas of high multiple hazard co-location are located within the Residential Red Zone, with large areas of the Zone being exposed to four or more hazards. The hazards within this zone also have the highest intensities, giving a high percentage coverage of combined extreme intensity multi-hazard. Based on this finding, any decisions on the future land use and potential re-development of these areas within the zone need to carefully consider a full range of multi hazards.

12.4 Key Gaps Identified

The gaps in the spatial analysis co-location primarily fall into the following two areas:

1. Gaps in the spatial coverage and intensity of the individual hazards at a range of comparable time scale that are appropriate for infrastructure and land-use planning. These gaps are addressed in the appropriate individual hazard sections, and are summarised in the summary recommendations.

2. Gaps in the knowledge about what intensity of non-flood hazards are significant for the exacerbation of flood hazards through either co-incidence or cascading of the hazard events. Again these gaps are addressed in the appropriate individual hazard sections, and are summarised in the summary recommendations.

PART THREE: MULTI-HAZARD CO-INCIDENCE AND CASCADING GAP ANALYSIS

13. Co-incidence and Cascading Multi-Hazards

As outlined earlier in this report, the temporal co-incidence of interest in this study is the occurrence of a non-flood hazards occurring at the same time and in the same place as a FPF event, such that the coincidence creates the trigger for a FPF event to occur, or increases the magnitude and extent of the FPF event. Cascading is the occurrence of a non flood hazard followed at some time later by a FPF event, in which the first hazard alters the geomorphologic conditions in such a degree that they trigger or exacerbate frequency, magnitude or extent of the FPF event.

13.1 Likelihood of Temporal Co-incidence of Hazards

The likelihood of temporal co-incidence is linked to the probability of the individual events and whether they are discrete (e.g. earthquake and flood) or linked events (e.g. storm surge and flood) where there is a degree of co-dependence on the occurrence of the two events at the same time. From the analysis of the individual hazards, the anticipated likelihood of temporal co-incidence is summarised in **Table 13-1**. As set out in section 5.3.4, the rankings of High, Medium and Low used in the Table are quantitative assessments assigned by the authors to representative the relative differences in likelihood and consequence. Probabilities of occurrence or magnitude of consequence have not attempted to be qualified.

Table 13-1 Anticipated likelihood and consequence of co-incidence of hazard types with FPF events

Hazard	Likelihood of Temporal Co-incidence with FPF Event	Consequence of Co-incidence for Exacerbating Flooding
Coastal Storm	High	High
Snow and Hail Event	Low	Moderate (blocked drains, change antecedent conditions)
Extreme Wind Event	Low (except for coastal storms)	Low (except for coastal storms)
Future Coastal Erosion	High	High
Future Coastal Inundation	High	High
Distant Source Tsunami	Low	High
Regional Source Tsunami	Low	High
Local Source Tsunami	Low	High
Local Christchurch Earthquake	Low	High
Regional Canterbury Earthquake	Low	High
Distant Southern Alps Earthquake	Low	High
High Ground water Levels	High	High
Hill slope Instability	Moderate (erosion in extreme rainfall event)	Low
Waimakariri Flood – stopbank contained	Low	Moderate (mouth migration)
Waimakariri Flood – stopbank breached	Low	High
Notes	(1) Except for extreme winds associated with coastal storms (2) As a result of sea level rise. Can be treated as a co-	

	incidence or a cascade (3) Mainly centred around extreme rainfall events in the Port Hills

13.2 Consequences of Key Co-incidences for Exacerbation of Flood Hazard

From the above summary the key temporal co-incidences of non-flood hazards and FPF events that require further investigation are:

- Coastal Storms
- Future Coastal Erosion
- Future Coastal Inundation
- High Ground Water Levels

13.3 Likelihood of Cascade of Hazards

The likelihood of cascade hazards is linked to the probability of both hazards occurring within some time period between the two hazards. This time period will vary for different hazard cascades. Table 13-2 summaries the anticipated likelihoods and consequences of the various cascades from non-flood hazard to FPF events. The linkage between likelihood and consequence is the degree of permanence to the geomorphic change from the non-flood hazard. As with Table 13-1, the rankings of High, Medium and Low used in the Table are quantitative assessments assigned by the authors to representative the relative differences in likelihood and consequence. Probabilities of occurrence or magnitude of consequence have not attempted to be qualified.

Table 13-2 Anticipated likelihood and consequence of cascade of hazard types to FPF events

Hazard	Cascade Likelihood	Cascade Geomorphic Permanence	Cascade Consequence for Exacerbating Flooding
Coastal Storm	High	Moderate (estuary/river mouth migration)	Moderate (estuary/river mouth migration)
Snow and Hail Event	Low	Nil	Low (only if very short term cascade of events)
Extreme Wind Event	Moderate	Nil	Nil
Future Coastal Erosion	High	High	High
Future Coastal Inundation	High	High	High
Distant Source Tsunami	Low	High (estuary/river mouth, estuary infrastructure)	High (estuary/river mouth, estuary infrastructure)
Regional Source Tsunami	Low	Moderate (less likelihood of permanent impacts)	Moderate

Hazard	Cascade Likelihood	Cascade Geomorphic Permanence	Cascade Consequence for Exacerbating Flooding
Local Source Tsunami	Low	Uncertain	Uncertain
Local Christchurch Earthquake	High	High (liquefaction, vertical displacement)	High
Regional Canterbury Earthquake	High	Moderate (liquefaction, vertical displacement)	Moderate
Distant Southern Alps Earthquake	High	Moderate (liquefaction, vertical displacement)	Moderate
Future High Ground water Levels	High	High permanent high water table	High
Hill slope instabilities	Moderate	High	Low limited ability to get in river channel/estuary
Waimakariri Flood-stopbank contained	Moderate	Moderate (mouth migration)	Moderate mouth migration)
Waimakariri Flood –stopbank breached	Low	Moderate	Moderate

13.4 Consequence of Key Cascades for Exacerbation of Flood Hazard

The key cascades with consequence for FPF events are identified as:

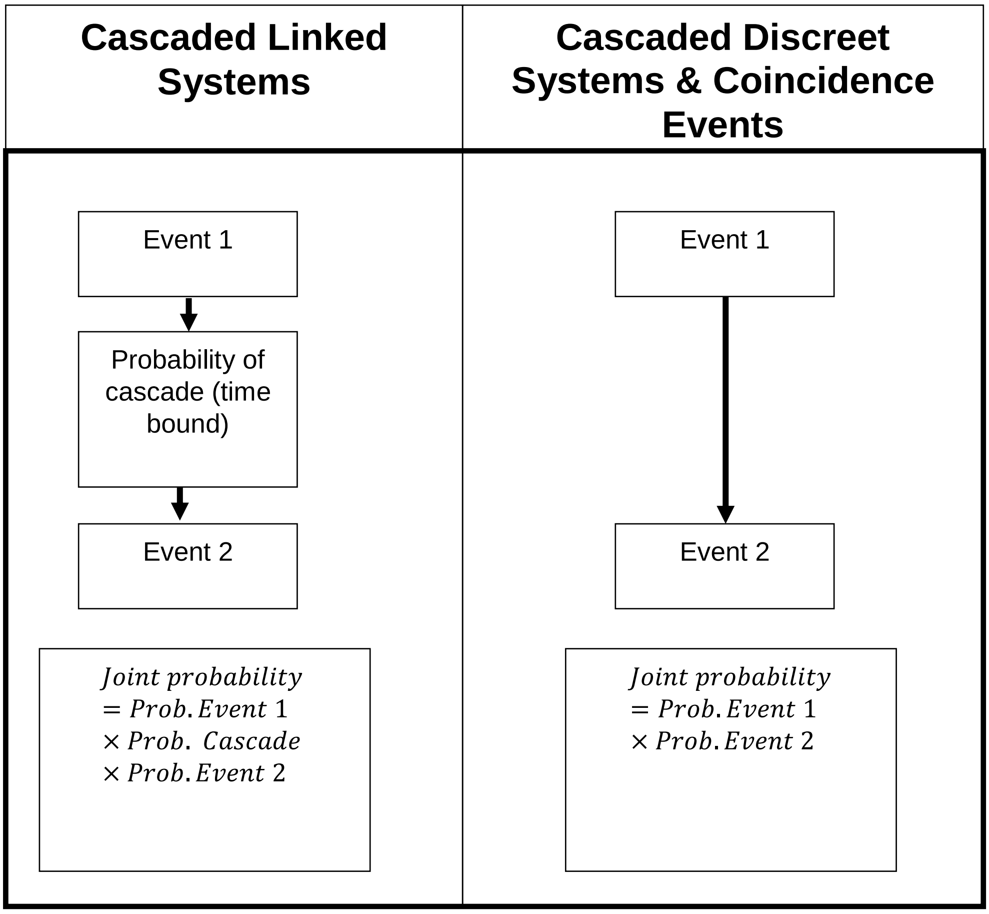
- Future coastal erosion
- Future coastal inundation
- Local Christchurch earthquakes

13.5 Joint Probabilities

Council has identified that LDRP97 is to investigate joint probability analysis in later stages in order to prioritise options. We have conceptually identified the following probability models in a multi-hazards context.

Joint probability for discreet and coincidence events is relatively simplistic in that probabilities can be multiplied; however, gaps do exist in identification of the probability to be used. A key focus of this study is to understand the effects of these events on flooding which then requires probabilities to be associated with a flood effect. For example; probabilities of certain earthquake events are known but these are generally with respect to ground damage or predicted forces. For this study the probability should be for predicted geomorphological change (e.g. vertical uplift or liquefaction) that in turn affects flood magnitude and extent. That probability is not known for Christchurch and is a gap in the information listed.

For linked systems the probability of a particular cascade occurring is not known and further study is required to better understand this occurrence. In light of this project scope a key focus is weather events that cause flooding and this has been identified as a priority study.



13.6 Key Multi-hazard Co-incidence and Cascade Gaps Identified

The gaps identified to investigate the consequences of co-incidences and cascades requires data gaps on the individual hazards to be filled, and the probability of coincidence and cascades to be determined. The Gaps identified are previously detailed in the relevant sections on the individual hazards of this report. Priority gaps are included in the recommended studies to be filled in stage two of the multi-hazards project (Report Section 15).

PART FOUR: ENGINEERING AND PLANNING RESPONSE GAP ANALYSIS

14. Engineering and Planning Response Gap Analysis

14.1 Introduction

This section reports a high-level review of the existing engineering, policy and planning information available to inform this project.

14.2 Policy

14.2.1 Whole of Life Analysis and Discount Rates

Stage 3 intends to use a net present value (NPV) analysis to compare the whole of life cost of different engineering and policy intervention options. This analysis will require estimates to be prepared for capital (build) costs, land access/purchase, capital renewals and operation and maintenance. Section 14.4.3 presents our review of existing cost information.

NPV analysis will also require a discount rate to be assumed. The discount rate determines the present value of future expenditure. The choice of discount rate can have a substantial effect on the value of future damage, damage avoided (benefits) and the cost of investment. A lower discount rate tends to result in higher benefit/cost ratios in flooding projects with a long appraisal period. This is especially true when considering flood defence schemes which involve costs in the short term and benefits accruing over the longer term. The higher the discount rate, the lower the influence of future expenditure on the NPV.

Treasury provides the following recommendations on discount rates for infrastructure projects (Table 14-1). The Treasury advice does not distinguish between different types of infrastructure or the purpose of the infrastructure.

A discount rate of 8% was applied to the whole of life analysis undertaken at SCIRT based on direction provided by Treasury. This was higher than the 5.6% rate proposed by CCC. The use of this higher rate reduced the influence of future expenditure (capital renewals, operation and maintenance) on the NPV. Following advice from the independent peer reviewer on the Stormwater Infrastructure Economics (LDRP504) project, a default value of 5% has so far been used for stormwater economic appraisals.

An international review of the appraisal of flood risk management schemes undertaken in LDRP504 revealed a distinct variance between discount rates applied internationally (Table 14-2). Generally, European countries apply lower discount rates to other countries indicating greater consideration of intergenerational equity and a lesser focus on the cost of capital, which may be a driver for the selection of discount rates.

Table 14-1 Treasury Recommendations for Infrastructure Project Discount Rates (source: http://www.treasury.govt.nz/publications/guidance/planning/costbenefitanalysis/currentdiscountrates)

Category	Rate
Default rate (for projects that are difficult to categorise including regulatory proposals):	6.0% p.a.
General purpose office and accommodation buildings	4.0% p.a.
Infrastructure and special purpose (single-use) buildings: Water and energy Prisons Hospitals Hospital energy plants Road and other transport projects	6.0% p.a.
Telecommunications, media and technology , IT and equipment, Knowledge economy (R&D)	7.0% p.a.

Table 14-2 Review of international approach to appraisal, metrics and discount rates

Country	Discount rates
UK	3.5% (reducing over time)
Ireland	4% (sensitivity analysis of 3%-5%)
Australia	7% (sensitivity analysis of 3% and 10%)
Canada	8% (sensitivity analysis of 3% and 10%)
European Union	3%-5%
United States	7%
New Zealand	Variable between 6-10%

An unresolved issue between economists and climate scientists is that, even at social discount rates of 2-3%, economists struggle to justify significant spending in the present to fight climate change. In the 2006 Economics of Climate Change: The Stern Review, a 0% discount rate was used to justify investment in the present to combat climate change but this is not broadly accepted as defendable by economists. In the UK's Flood and Coastal Erosion Risk Management Appraisal Guidance, UK Treasury variable discount rate is used: 3.5% in years 0 to 30, 3% from years 31 to 75 and 2.5% from year 76 to 99, for a 100 year appraisal. This guidance assumes both costs and benefits are discounted at the same rate.

Ideally, NZ Treasury would provide guidance on different discount rates for different kinds of infrastructure, including infrastructure for mitigating flooding and the effects of climate change mitigation. However this information is not currently available. In the absence of Treasury guidance, Council should develop its own policy on the discount rates used in flood management appraisals which then allow consistent appraisal across different studies. It is noted that if Council chooses a different value than Treasury, it may affect any future cost sharing with the Crown.

It is also noted that the Council does not have a policy on targeting funding of schemes according to communities ability to pay. For example, a standard economic appraisal based on market property values will accrue greater damages in affluent areas which can then justify greater spend in these areas. Alternatively, it could be Council's policy to preferentially support more deprived areas which are less able to demonstrate the economic benefits or to contribute to schemes. Setting such a long-term policy is important to management of natural hazards which, in Christchurch, could be focussed in the eastern areas, some of which are less affluent.

Based on the information currently available a discount rate of 5%, in accordance with the independent economist advice obtained during LDRP504 is proposed to be used for the NPV analysis in Stage 3. However, it is recommended that Council works with Treasury to determine a longer-term policy for setting discount rates and undertaking economic appraisals for natural hazard response.

14.2.2 Residential Red Zone

The Residential Red Zone (RRZ) is land where the earthquake land damage and risk of future earthquake land damage is such that it has been deemed inappropriate for residential use in its current form. Regenerate Christchurch (an entity formed by the Crown and Council) is leading the regeneration of the RRZ. At time of writing, no decisions have been made over the use of RRZ land, with a number of proposed uses suggested by different community groups.

In addition to the liquefaction and lateral spreading risk which led to its zoning, the RRZ is also subject to a number of other hazards including flooding, with much of the RRZ subject to multiple hazards. Decisions about the future use of the RRZ should consider multi-hazards and the tenability of land to be reoccupied.

The different options for future RRZ land could result in the following outcomes with respect to floodplain management:

1. RRZ stays as residential.
2. RRZ is used for recreation spaces, non-habitable facilities or flood plain management.
3. RRZ undergoes intensive development.
4. A mix of land uses.

The different land uses being considered could result in no change to floodplain management over these areas, could provide opportunities for integrating capacity upgrades/ storage/treatment that could benefit floodplain management, or could result in intensive development that makes floodplain management more difficult. However, since any land use change should require planning approval, it is expected that effects will be mitigated through the planning process.

In the absence of any decision over the use of the RRZ, for the purposes of considering options in Stage 3 of this project will assume that RRZ land use will be as it was before the 2010/11 earthquakes. This is consistent the approach taken by Council and SCIRT for sizing other post-earthquake infrastructure (e.g. replacement terminal wastewater pump stations). Retreat

Christchurch, in common with most coastal areas, is currently managing future risk of extreme weather and erosion by building flood defences, reinforcing infrastructure and establishing building codes (Hino, Field and Mach (2017)). However, managed retreat is often discussed as a possible future option and LDRP97 aims to develop a clear understanding of selective retreat or managed realignment at the coast. We are not aware of any Council policy on managed retreat from land prone to flooding or other natural hazards, or studies which have specifically considered this a controversial option, although there are examples from elsewhere in New Zealand and internationally.

This project aims to consider managed retreat in combination with both hard and soft engineering options, and therefore requires an equivalent level of information on which to base appraisals. Even at a high level, engineering options are typically scoped, costed and assessed using multiple criteria. Managed retreat is here considered differently from e.g. the Flood Intervention Policy (CCC) due to the likely larger scale of retreat from low lying eastern city coastal areas. Indeed, Preparing for Rising Seas (Parliamentary Commissioner for the Environment (2015)) recognises that large scale managed retreat will be the highest cost responses and require local and central government financial assistance.

However, there are many different ways that managed retreat could be implemented and this should be defined before being considered as an option alongside others, for example:

- Individual areas or wide scale retreat?
- Voluntary sale or compulsory purchase?
- Council lease back buildings for a limited time or demolish?
- Create new area to possibly retreat to?
- What would the area retreated from be used for?

Hino et al. (2017) review 27 documented cases of managed retreat which have been undertaken as a response to climate risks or natural hazards; these typically involve residents moving and a government agency implementing the move. Based on the case studies, two key factors defining the experience of retreat are who initiates the move and who benefits from it. Cases are cited where lack of government support crippled implementation of retreat and recognition that by some metrics, benefits may not outweigh the costs.

Within New Zealand, there are a number of studies from which lessons could be learned. In the Kapiti Coast Proposed District Plan (PDP), retreat was proposed but ultimately the maps and provisions relating to Coastal Hazard Management Areas were withdrawn (Kapiti Coast District Council District Plan Review). Contributing factors included insufficient consultation with affected parties and science to back up the proposition.

In Preparing for Rising Seas, Dunedin City Council is reported to be investigating forms of managed retreat which could become analogous to the red zoning in Christchurch, although over a longer time frame.

The need for further research into the viability of retreat and how it can be successfully implemented was identified in the LGNZ Managing natural hazard risk in New Zealand report (Local Government New Zealand (2014). We are not aware that such research has been undertaken.

In the absence of a retreat policy, a number of assumptions will need to be made to develop managed retreat options for Stage 3. However, we recommend that Council undertakes a project to specifically define the ‘shape’ of a managed retreat option for Christchurch, so that this can be effectively considered alongside other possible options.

14.2.3 Property Purchase

Council’s Flood Intervention Policy offers eligible residential properties, at risk of flooding in a 10 year ARI post-earthquake scenario and where this flooding has been exacerbated by the CES, the opportunity to sell their properties to the Council if no catchment works are delivered in a timely manner. It is anticipated, however, that this policy is targeted at resolving relatively isolated issues and will not be used for more widespread managed retreat scenarios.

The Public Works Act set outs the process for acquiring land for public works, which would apply to engineering mitigation options.

We are not aware of any existing Council policy on property purchase for managed retreat, i.e. whether or not properties would be purchased by Council, and if purchased based on what valuation. This relates both to private property and RRZ land (which is currently owned by the Crown). This affects the capital cost estimates and NPV of options as part of Stage 3.Policy Gap Summary

Gaps in policy are presented in Table 14-3.

Table 14-3 Policy Gap Summary

Gap Description	Benefit if Addressed / Risk if not Addressed	Indicative Budget Estimate and Timescale Required
<u>Policy on discount rate</u> There is no Crown or Council policy specifically on the discount rate for infrastructure for flood mitigation or mitigation of climate change effects. In the absence of specific Treasury guidance on discount rate for infrastructure of 6% will be used.	The discount rate adopted affects the NPV, with a higher discount rate reducing the effect of future expenditure on the NPV.	Budget Estimate: Low- Treasury or Council Requirement: Outside project
<u>Policy on options assessment</u> There is no national policy or Council policy on managed retreat, including when retreat may be considered, mechanisms/processes and timeframes. As there are significant community and social issues associated with retreat, options would need to be developed in consultation with the community.	Benefit: Stage 3 will include consideration of managed retreat and engineering mitigation options. Risk: Without understanding policy for retreat options a number of assumptions will need to be made including triggers, timeframes and costs of retreat options, leading to lower confidence in the conclusions.	Budget Estimate: High (three aspects can be undertaken as one study) Requirement: Within project
<u>Council policy on property purchase</u> While Public Works Act set outs the process for acquiring land for public works (which would include engineering mitigation options), we are not aware of any existing Council policy on purchase of private property for managed retreat.	Approach affects the Stage 3 cost estimates. If there is no policy, then a range of options need to be considered from no property purchase to purchase at current rating valuation.	
<u>Council policy on Residential Red Zone land purchase</u> We are not aware of any existing Council policy on purchase of RRZ (currently owned by the Crown) for engineering mitigation or managed retreat.	Approach affects the Stage 3 cost estimates. If there is no policy then a range of options needs to be considered from no Red Zone payment to purchase of Red Zone land at current rating valuation.	

14.2.4 Policy References

Christchurch City Council. (n.d.). *Flooding Intervention Policy*. Retrieved from : https://www.ccc.govt.nz/the-council/plans-strategies-policies-and-bylaws/policies/sustainability-policies/flooding-intervention-policy/

Kāpiti Coast District Council. (n.d.). *District Plan Review.* Retrieved from: http://www.kcdc.govt.nz/Your-Council/Planning/District-Plan-Review/

Local Government New Zealand. (2014). *Managing natural hazard risk in New Zealand – towards more resilient communities.* Wellington, New Zealand.

Hino, M., Field, C. B., & Mach, K. J. (2017). Managed retreat as a response to natural hazard risk. *Nature Climate Change*, *7*, 364–370

Parliamentary Commissioner for the Environment. (2015). *Preparing New Zealand for rising seas: Certainty and Uncertainty.*

14.3 Planning

14.3.1 Introduction

The following is an overview of the planning framework for managing flooding and other natural hazards, including policy direction at a national, regional and district level, the focus being on the four project areas.

14.3.2 National Planning Framework

A number of different Acts are relevant to hazard management, including the Resource Management Act (RMA) 1991, Local Government Act 2002, Building Act 2004, and Civil Defence and Emergency Management Act 2002.

The purpose of the Resource Management Act (Section 5) is the sustainable management of natural and physical resources in a way, or at a rate that enables people and communities to provide for their social, economic and cultural well-being and their health and safety. Particular regard is to be had to a range of matters including the effects of climate change (Section 7).

Under the RMA both Regional and District Councils have functions for managing natural hazards. Relevant excerpts from the Act are outlined below:

Section 31(1): Every territorial authority shall have the following functions for the purpose of giving effect to this Act in its district:

a) The establishment, implementation, and review of objectives, policies, and methods to achieve integrated management of the effects of the use, development, or protection of land and associated natural and physical resources of the district:
b) The control of any actual or potential effects of the use, development, or protection of land, including for the purpose of –
    (i) the avoidance or mitigation of natural hazards.

Section 30(1): Every regional council shall have the following functions for the purpose of giving effect to this Act in its region:

c) The establishment, implementation, and review of objectives, policies, and methods to achieve integrated management of the natural and physical resources of the region:
d) The preparation of objectives and policies in relation to any actual or potential effects of the use, development, or protection of land which are of regional significance:
e) The control of the use of land for the purpose of-
    (vi) the avoidance or mitigation of natural hazards.

The Resource Legislation Amendment Bill proposes the addition of 'the management of significant risks from natural hazards' to section 6 of the RMA as a matter of national importance. Plans prepared under the RMA would need to recognise and provide for this in managing hazards in the areas subject to this gap analysis.

The Government's indication of future policy direction (A Way Forward for National Direction, 2016) includes the intent to prepare a National Policy Statement on Natural Hazards, with an expected completion date of 2018.

Existing national policy direction on coastal hazards is provided in the New Zealand Coastal Policy Statement 2010. This is relevant to those areas affected by coastal hazards, including parts of the four areas identified for this project. Of particular relevance, Policies 24 to 27 of the NZCPS deal with the identification of coastal hazards and their management through defence, land use and development (refer to Appendix A for these policies).

- Policy 24 Identification of coastal hazards.
- Policy 25 Subdivision, use and development in areas of coastal hazard risk.
- Policy 26 Natural defences against coastal hazards.
- Policy 27 Strategies for protecting significant existing development from coastal hazards.

14.3.3 Regional Planning Framework

The Canterbury Regional Policy Statement (CRPS) provides a regional framework for the management of natural hazards, particularly Chapter 11 Natural Hazards. Relevant objectives and policies from Chapter 11 are included in Appendix A.

Of particular relevance, Policy 11.3.1 of the CRPS seeks "*To avoid new subdivision, use and development (except as provided for in Policy 11.3.4) of land in high hazard areas*". Outside these areas, policy 11.3.2 seeks the avoidance of new subdivision, use and development (excluding critical infrastructure) in areas subject to inundation by a 0.5% AEP flood event, unless there is no increased risk to life, and subdivision, use and development meets other criteria.

In terms of the management of hazards, policy 11.3.6 seeks recognition of the role of natural features and vegetation and their maintenance, protection and restoration. Policy 11.3.7 has limitations on new physical works to mitigate hazards with consideration to be given to alternatives such as relocation, removal or abandonment. In respect of Policy 11.3.7, criteria specify the circumstances where new physical works are acceptable. This includes situations where the natural hazard risk cannot be reasonably avoided or adverse effects on the environment are avoided, remedied or mitigated.

The Regional Coastal Environment Plan sets out issues relating to the protection, development and enhancement of the Coastal Marine Area and the coastal environment, with Chapter 9 dealing with hazards from coastal erosion and seawater inundation.

14.3.4 Canterbury Water Management Strategy and Zone Implementation Programme

The Christchurch West Melton Zone Implementation Programme (ZIP) was developed under the Canterbury Water Management Strategy (CWMS) in 2013. Its geographic scope includes the catchments of the Heathcote River/Ōpāwaho, Styx River/Pūharakekenui, Avon River/Ōtākaro and Avon-Heathcote Estuary/Ihutai. It sets out priority issues, outcomes and recommendations for the Christchurch West Melton area.

'Enhancing and Managing Waterways for Recreation, Relaxation and Amenity' is one of five priority issues identified by the Christchurch West Melton Zone Committee to address in their ZIP. Priority outcomes have been identified under this issue, which include providing for multiple recreation, relaxation and amenity uses. A second outcome of relevance is reducing and eliminating any adverse effects of flood management activities on the safety of water based recreation. To achieve this, a recommendation is made in the ZIP to review statutory plans and flood management programmes to achieve the outcome.

Recommendations also include progressing the Mid-Heathcote River/Ōpawaho Linear Park Masterplan (discussed below), developing a coordinated programme to establish a multiple use park along the Avon/Ōtākaro River, as well as to:

> "*Investigate a coordinated programme of actions to move flood protection banks further back from urban waterways to facilitate improved recreation, relaxation and amenity*".

A second priority issue is 'Improving Surface Water Quality and Safeguarding Surface Water Flows'. A relevant priority outcome is to reduce stormwater impacts on surface water quality. Management of stormwater also has impacts on flood management, and a subsequent recommendation is to:

> "*Identify and implement performance standards for the permeability of new and resurfaced carparks/ footpaths/drives to reduce run-off rates*"

A third priority issue is ‘Enhancing Degraded Ecosystems, Indigenous Biodiversity, Valued Introduced Species and Landscapes’. A relevant priority outcome includes minimising the effects of flood management activities on water biodiversity. The subsequent recommendation is to:

“*3.1 a) Continuously improve work programmes and operations to:*

- *Minimise the direct impacts of flood management operations on biodiversity*
- *Rehabilitate waterways after modification to increase the diversity of in-stream habitat*”.

14.3.5 Christchurch City Council

Christchurch City Council has a framework of strategies, plans and policies providing direction for managing hazards across the City and the four areas defined for this project. The documents described below are of particular relevance.

Christchurch District Plan

The Christchurch District Plan (CDP) is effectively operative, following a truncated process to review the previous City Plan over a period from 2013 to the present. This has been prepared in the context of a planning framework that reflects the effects of the earthquake, including the Land Use Recovery Plan and Chapter 6 of the Canterbury Regional Policy Statement.

The Natural Hazards chapter (Chapter 5) of the District Plan is now operative. This chapter provides a policy framework and rules for managing a range of hazards in giving effect to the CRPS policies. Overlays define the extent of different hazards including the following:

- Flooding;
- Slope instability;
- Cliff Collapse;
- Rockfall; and
- Mass movement.

For the four defined areas, the following table provides an overview of the relevant layers:

Table 14-4: Overlays of the Christchurch District Plan in the project study areas.

	Overlay in the Christchurch District Plan												
Area	FMA	FMLO	FPMA	HFHMA	PHBPSIMA	CCMA1	CCMA2	RMA1	RMA2	MMMA1	MMMA2	RUHFHMA	LMA
Avon River up to Barbadoes Street	✓	✓	✓	✓								✓	✓
Heathcote River up to Colombo Street and City Outfall Drain	✓	✓		✓	✓			✓	✓		✓		✓
Southshore and Estuary	✓	✓		✓	✓	✓	✓			✓	✓	✓	✓
Lower Styx River The Styx River up to Marshlands Road	✓	✓	✓	✓									✓

Key: Flood Management Area (FMA); Fixed Minimum Floor Level Overlay (FMLO); Flood Ponding Management Area (FPMA); High Flood Hazard Management Areas (HFHMA); Remainder of Port Hills and Banks Peninsula Slope Instability Management Area (PHBPSIMA); Cliff Collapse Management Area 1 (CCMA1); Cliff Collapse Management Area 2 (CCMA2); Rockfall Management Area 1 (RMA1); Rockfall Management Area 2 (RMA2); Mass Movement Management Area 1 (MMMA1); Mass Movement Management Area 2 (MMMA2); Residential Unit Overlay with the High Flood Hazard Management area (RUHFHMA); Liquefaction Management Area (LMA).

Of particular relevance to this project, Council as part of the District Plan Review notified provisions for managing coastal hazards including the use of the following overlays:

- Coastal Erosion Management Areas; and
- Coastal Inundation Management Areas.

Following notification of provisions for Coastal Hazards, the Government removed these from the Council's district plan review process by way of an Order in Council, which came into force on Friday 16 October 2015.

The CDP has a range of provisions in the Residential, Commercial, Industrial and Subdivision chapters to provide for intensification of existing urban areas, and zones new greenfield areas for residential, commercial and industrial development.

Outline Development Plans (ODPs) for greenfield areas identified for residential, commercial and industrial development include the identification of areas for stormwater treatment and retention. In some cases, these depict the location anticipated for stormwater facilities to manage stormwater. In some instances, rules in chapters of the District Plan also specify requirements for stormwater design in greenfield areas. Also, through the administration of Council's global resource consents for the discharge of stormwater to the Heathcote River/ Ōpāwaho and Styx river/Pūharakekenui, (including the SMPs which form part of the resource consents), Council can define the parameters of stormwater design for greenfield areas subject to ODPs, supporting implementation of the District Plan.

There are two outcomes influenced by the District Plan that may result in a higher rate of discharge of stormwater from the catchments of the Heathcote, Avon and Styx rivers. These are:

1. the intensification of existing urban areas through rezoning for higher density living, and

2. the increased extent of impermeable surfaces in residential, commercial and industrial zones through changes to rules controlling site coverage/ plot ratios.

An assessment of the effects of new development can be undertaken by Council for Discretionary and Non-complying activities and where specified as matters of control/ discretion for controlled/ restricted discretionary activities. It is not otherwise considered through the District Plan.

Surface Water Strategy 2009

The purpose of the Surface Water Strategy 2009 is to direct the Christchurch City Council's decision making in relation to the management of surface water. The strategy establishes the surface water goals for the next 30 years, including how the Council is managing flood risk and reducing the adverse effects of flooding.

Implementation of the Surface Water Strategy has been achieved in part through the preparation and implementation of Stormwater Management Plans (SMPs), which seek to achieve an integrated approach to managing stormwater and improvements in the six values of drainage, ecology, cultural values, recreation, heritage and landscape. Stormwater Management Plans are in place for the Heathcote (South West Christchurch) and Styx River catchments.

14.3.6 Land Drainage Recovery Programme

The Land Drainage Recovery Programme (LDRP) involves assessment of damage to waterways and their margins as a consequence of the sequence of earthquakes, and where necessary, reducing flood risk and making improvements to bank stability.

14.3.7 Other strategies

Other strategies of relevance include:

- Resilient Greater Christchurch Plan – Provides a vision, principles and actions for building resilience in Greater Christchurch, including an action to “Develop a risk reduction framework to help us invest efficiently in interventions around our threats and hazards”.
- Climate Smart Strategy 2010 – 2025;
- Heathcote River Floodplain Management Strategy 1998 – A non-statutory document to guide decisions of Christchurch City Council and Canterbury Regional Council on managing flood risk.
- Flooding Intervention Policy – Programme to assist *“property owners whose homes are at risk from flooding during regular rainfall events, where the earthquakes have worsened this risk, and the home will not benefit from timely, area-wide engineering works to reduce the risk”.*
- Suburban Centre Master Plans including Ferry Road Master Plan, Main Road Master Plan, Linwood Village Master Plan, New Brighton Centre Master Plan, and Sumner Master Plan.

14.3.8 Planning Gap Summary

Table 14-5 summarises key gaps which could be filled either to progress this project (i.e. required within project – shaded green), or to progress future work connected with this project (i.e. required beyond project – shaded orange). Those required within this project are listed at the top of the table. Indicative budget estimates are classified according to: low <$20k, medium: $20 – $50k, high: > $50k.

Please note that budget estimates cannot be provided for the gaps, which are beyond our knowledge/ control i.e. those responsible for addressing the gaps are Christchurch City Council’s Strategy and Planning Group and the Ministry for the Environment.

Table 14-5 Gaps relevant to improving planning for flood management in the Heathcote Catchment

Gap Description	Benefit if Addressed/Risk if not Addressed	Indicative Budget Estimate Timescale Required
District Plan Provisions for managing coastal hazards	**Benefit**: Certainty for managing activities in areas at risk of erosion and/or inundation. **Risk**: The absence of provisions for managing coastal hazards creates uncertainty and the inability to consider regulatory requirements at a Christchurch level. Assumptions may need to be made regarding how CCC will manage coastal hazards/ sea level rise, having regard to strategies/ plans of the Council. Following the introduction of a regulatory framework, there is a risk that work completed up til then is not to the new standard.	**Budget Estimate:** Unknown (Responsibility of Strategy and Planning group of Council) **Requirement:** Outside scope of project
National Policy Direction on managing natural hazards	**Benefit:** Clarity of approach to be applied nationally to the management of natural hazards **Risk:** Upon the introduction of national policy/ standards, there may be requirements for managing natural hazards to a higher standard. Work completed up til the introduction of national policy/ standards will not account for new requirements and changes may be required in any design and/ recommendations.	**Budget Estimate:** Unknown (Responsibility of Ministry for the Environment) **Requirement:** Outside scope of project.

14.3.9 References and Information Sources for Planning Review

Christchurch City Council and Canterbury Regional Council (1998) *Heathcote River Floodplain Management Strategy*. Retrieved from: http://ecan.govt.nz/publications/Plans/HeathcoteRiverFloodplainManagementStrategy.pdf

Christchurch City Council (2016) *Flood Intervention Policy*. Retrieved from: http://www.ccc.govt.nz/the-council/plansstrategies-policies-and bylaws/policies/sustainability-policies/floodingintervention-policy/

Christchurch City Council (2017). *Christchurch District Plan, Chapter 8 Subdivision, Development and Earthworks, 8.6 Appendices*. Retrieved from: http://districtplan.ccc.govt.nz/pages/plan/book.aspx?exhibit=DistrictPlan

Christchurch City Council (2015) *Long Term Plan 2015 – 2025*. July 2015 [Including Flood Protection and Control Works. Activity Management Plan. As amended through the Annual Plan 2016/17 July 2016; and Stormwater Drainage Activity Management Plan]. Retrieved from: https://www.ccc.govt.nz/the-council/plansstrategies-policies-and-bylaws/plans/long-termplan-and-annual-plans/long-term-plan-2015-25/

Christchurch City Council (2009) *Christchurch Mid-Heathcote River / Ōpāwaho. A Vision For The Long Term Protection And Enhancement Of One Of Christchurch's Key Natural Assets*. Final Document. Retrieved from https://www.ccc.govt.nz/assets/Documents/The-Council/Plans-Strategies-Policies-Bylaws/Plans/Park-management plans/MidHeathcoteRiverOpawahoMasterplan.pdf

Christchurch City Council (2009) *South-West Christchurch Area Plan*. Retrieved from: https://www.ccc.govt.nz/the-council/plansstrategies-policies-and-bylaws/plans/areaplans/south-west-area-plan

Christchurch City Council (2009) *Belfast Area Plan*. June 2010. Retrieved from: https://www.ccc.govt.nz/the-council/plans-strategies-policies-and-bylaws/plans/area-plans/belfast-area-plan

Christchurch City Council. *Chapter 5 Natural Hazards.* Retrieved from: https://districtplan.ccc.govt.nz/pages/plan/book.aspx?exhibit=DistrictPlan.

Christchurch City Council (2014) *Water Supply, Wastewater and Stormwater Bylaw 2014*. Retrieved from: https://www.ccc.govt.nz/assets/Documents/The-Council/Plans-Strategies-Policies-Bylaws/Bylaws/ChristchurchCityCouncilWatersupplyWastewaterandStormwaterBylaw2014.pdf.

Christchurch City Council (2003) *Waterways, Wetlands and Drainage Guide*. Retrieved from: https://www.ccc.govt.nz/environment/water/water-policy-and-strategy/waterways-wetlands-anddrainage-guide

Christchurch City Council. *Suburban Centres Master Plan Programme*. Retrieved from: https://ccc.govt.nz/the-council/plans-strategies-policies-and-bylaws/plans/suburban-plans/

Environment Canterbury (2013) *Canterbury Regional Council Flood Protection and Drainage Bylaw 2013*. April 2013. Retrieved from: http://ecan.govt.nz/publications/Plans/floodprotection-drainage-bylaw-2013.pdf

Ministry for the Environment (2016). *A way forward for national direction – 2016* http://www.mfe.govt.nz/sites/default/files/media/RMA/MFE_RMA%20Nat%20Direction_Lo-Res.pdf

14.4 Engineering

The existing engineering studies and available information on existing engineering infrastructure have been provided by CCC and are presented in **Appendix D**.

14.4.1 Existing and Proposed Infrastructure

Existing Infrastructure

The existing critical flood infrastructure in the project areas includes:

- Stormwater reticulation and stormwater pump stations (all project areas).
- Subsoils/field tiles and groundwater pump stations (all project areas).
- Avon River stopbanks (Avon River).
- Woolston barrage (Heathcote River).

The Christchurch City Council District Plan defines critical infrastructure as:

"*infrastructure necessary to provide services which, if interrupted, would have a serious effect on the communities in Christchurch District and which would require immediate reinstatement. This includes any structures that support, protect or form part of critical infrastructure. It includes:*

1. *Christchurch International Airport;*
2. *Lyttelton Port of Christchurch;*
3. *gas storage and distribution facilities;*
4. *electricity sub-stations, networks and distribution installations, including the electricity distribution network;*
5. *supply and treatment of water for public supply;*
6. *storm water and sewage disposal systems;*
7. *telecommunications and radio communications installations and networks;*
8. *strategic road network and rail networks (as defined in the Canterbury Regional Land Transport Strategy);*
9. *petroleum storage and supply facilities;*
10. *public health care facilities, including hospitals and medical centres;*
11. *emergency service facilities; and*
12. *New Zealand Defence Force facilities.*"

The presence of these assets within the study areas has not been investigated as part of this report, and is identified as a gap.

Proposed infrastructure from previous investigations

Proposed infrastructure from previous engineering studies includes:

- Additional stormwater pump stations (all project areas) - locations to be determined.
- Avon River stopbanks (Avon River) - recommended alignment for current land use is defined in Avon Stopbanks Refinement report.
- Heathcote River stopbanks and flood walls - locations to be determined.
- Styx River stopbanks and back flow prevention - locations to be determined.

These options will be included in the options considered as part of this study.

Investigated but not currently proposed infrastructure

Infrastructure which has had some investigation, but is not currently recommended/proposed includes:

- Tidal Barrier.
- Avon and Heathcote River Mouth Pump Stations.

It is assumed that these will not be revisited in the options considered as part of Stage 3 of this study.

Tidal Barrier

The Avon-Heathcote Tidal Barrier Pre-Feasibility Study in 2015 considered the technical feasibility, costs and (at a high level) the other effects of a tidal barrier at the Estuary mouth. It considered two sea level rise horizons: current sea level and 1 m sea level rise, and a 100 year storm event. It concluded that a tidal barrier was technically feasible, with an estimated capital cost of $310 m; however, other flood mitigation works would still be required. It noted that a tidal barrier would have significant landscape and visual amenity effects.

It concluded that the cost of a tidal barrier outweighed the benefits for current sea level, but that it would provide significant benefit in the future (1m sea level rise) scenario. The study also noted that it did not consider the tidal barrier in comparison with other engineering mitigation and planning (retreat) options, with climate change over time.

The Peer Review agreed with these points, and the Cost Estimate Peer Review agreed with an estimate range of $300 m to $350 m.

Following the Pre-Feasibility Report, Council carried out community consultation regarding the Tidal Barrier and reported to a Council Meeting on 29 October 2015. The Council meeting resolved that:

"8.4.1 A full feasibility study on a tidal barrier does not proceed at this stage, noting that feedback from a range of organisations did not support a full feasibility study.

8.4.2 It continue to work closely with CERA on the options for flood plain management as part of the technical work on the future use of the residential red zone.

8.4.3 It note that staff will utilise all of the information that was provided in the prefeasibility study in developing the Three Water Strategy."

It is noted that the wording of this resolution is specifically against proceeding with a feasibility study at that point in time, rather than precluding any future further consideration of a tidal barrier option. However, it would appear that the intent of the resolution is that a tidal barrier is not preferred, and further consideration of a tidal barrier in the short term is not supported. We therefore do not propose to include an Avon-Heathcote Estuary tidal barrier in the options considered in Stage 3. However, it is recommended that the business case for the tidal barrier is revisited in the future once (i) managed retreat is better defined as an option and (ii) Council's adaptive decision making strategy is defined in the anticipated Integrated Water Strategy.

Avon and Heathcote River Mouth Pump Stations

A high level investigation was carried out into the option of pump stations at the Avon and Heathcote River mouths, as an alternative to a tidal barrier. This is summarised in the River Mouth Pump Stations Memo from GHD to CCC, dated May 2015. It notes river mouth pump stations are considered feasible (based on other large pump stations around the world), but notes that the Estuary would not be protected by this option.

We understand that Council has not pursued river mouth pump station options further. We are not aware of any further work or community consultation on this option. While pump stations at the Avon and Heathcote river mouths may be technically feasible, they would present a number of similar issues to the Estuary tidal barrier. We therefore do not propose to include Avon and Heathcote river mouth pump stations in the options considered in Stage 3. However, pump stations at tributary mouths and stormwater outfalls will be included in the options considered in Stage 3.

SCIRT

SCIRT project works are essentially complete. Designs have been developed in accordance with the Infrastructure Recovery Technical Standards and Guidelines (IRTSG). A list of projects SCIRT has completed that may have an impact on flood hazard management are included in Appendix C. Also included are the design standards of each SCIRT project. Detailed information can be found on these projects and no information gaps have been identified.

14.4.2 Performance, Level of Service & Design Life

Stopbanks and Flood Walls

From the Avon Stopbanks Refinement report the proposed level of service for the new Avon River stopbanks is 1% AEP flood with climate change (16% increase in rainfall intensity and 1m sea level rise) plus 400 mm freeboard. The level of service for seismic settlement is up to 400mm settlement in a future ULS event. Wider application of these levels of service for stopbank level and seismic performance would need to be confirmed by CCC.

The level of service and design life for stopbanks and flood walls, which protect properties from fluvial or Estuary flooding, needs to be confirmed before concept design of mitigation options can be progressed in Stage 3. Both level and seismic performance levels needs to be confirmed.

Reticulation, Basins and Pump Stations

We are not aware of any information on the design level of service or performance of the existing stormwater reticulation, basins and pump stations.

From the WWDG and IDS the design standard for stormwater reticulation is generally designed so that the primary system (kerb and channel flow and pipe flow) is designed for the 5 year event, and the secondary system (overland flow paths, generally along road corridors) is designed for the 50 year event.

The design standard for new stormwater treatment and attenuation basins is set out in the Stormwater Management Plan (SMP) for each catchment. Stormwater attenuation ponds in new developments are generally designed for a 50 year event.

The level of service and design life for stormwater reticulation, basins and pump stations systems, which protect properties from pluvial flooding, needs to be confirmed before concept design of mitigation options can be progressed in Stage 3. This will assist in better defining costs of options.

Groundwater Management

We are not aware of any information on the design level of service defined for groundwater management. This needs to be defined before concept design of mitigation options can be progressed in Stage 3.

14.4.3 Capital Costs

Capital cost information will be used in Stage 3 of this study to:

- Inform estimates of proposed mitigation infrastructure.
- Understand the cost of land acquisition in realignment options.
- Understand the cost to Council in abandoning or altering its assets where necessary due to mitigation infrastructure or realignment.
- Understand the cost to Council in abandoning or altering other utilities where necessary due to mitigation infrastructure or realignment.

Existing CCC Engineering Infrastructure

CCC stormwater asset valuation data has been provided for the existing stormwater infrastructure. However:

- Recent stormwater assets (e.g. PS229, PS230 and PS231 constructed by SCIRT) are not included in the asset valuation data provided.

- Other CCC assets would also be affected by mitigation or realignment options including water, wastewater, roading and community facilities.

Valuation data of all current CCC assets within the project areas, including water, wastewater, stormwater roading and community facilities, should be considered as part of this assessment.

It is not clear whether the CCC valuation data reflects current construction costs, including post-earthquake escalation in construction cost and changes in seismic design (e.g. additional foundation costs for new pump stations).

Recent actual construction cost information for stopbanks and pump stations would provide a useful reference to inform cost estimates.

The depreciated or residual asset values are not included in the asset data provided. This data would be used in Stage 3 of this study to understand the cost to Council in abandoning assets due to mitigation or realignment.

Proposed CCC Engineering Infrastructure

Engineering estimates for stopbanks, including detailed cost breakdowns, are provided in the Avon Stopbanks Refinements report. These will be used as a reference in Stage 3.

High level cost estimates for stopbanks and pump stations are included in the Stage 1 River and Tidal Flood Protection studies. These do not have any cost breakdown and as such are of limited value to this project.

Engineering estimates for the Tidal Barrier are included in the report provided; however these are not directly relevant as a tidal barrier will not be included in the options considered in Stage 3 of this study.

Other Existing Utilities

While information on existing utilities is available through the SCIRT GIS, we do not have any information on the capital value of these assets.

There is also no information on CCC's policy on cost sharing for abandoning or replacing other utilities (e.g. power, telecoms, gas).

These issues need to be addressed with the costs associated with abandoning or replacing other utilities are to be included in the cost estimates as part of Stage 3 of this study.

14.4.4 Operation and Maintenance Costs

CCC stormwater operation and maintenance budgets have been provided. However, these are high level budgets (e.g. net pump stations maintenance or stopbanks maintenance) and do not include breakdowns or unit cost (e.g. per annum operation and maintenance cost per pump station or per metre length of stopbank).

If operation and maintenance costs are to be included in the NPV calculations as part of Stage 3, then operation and maintenance costs need to be available in a more useable form.

14.4.5 Engineering Gap Summary

Table 14-6 Gaps Relevant to Engineering and Infrastructure

Gap Description	Benefit if Addressed / Risk if not Addressed	Indicative Budget Estimate and Timescale Required
Levels of service for stormwater and flood mitigation infrastructure Confirmation of: • 2% AEP level of service for pump stations • 1% AEP plus climate change plus 400mm freeboard for stopbanks and flood walls. • Up to 400mm settlement of stopbanks in a ULS event	Level of service needs to be defined before carrying out concept design for pump stations and stopbanks/flood walls in Stage 3.	Budget Estimate: Low Requirement: Within study
Levels of service for groundwater management There is currently no level of service for managing groundwater. This needs to be defined before concept design sizing of groundwater management infrastructure can be undertaken as part of Stage 3. This should be provided by LDRP45.	Benefit: Level of service needs to be defined before carrying out concept design for groundwater management in Stage 3. Risk: Inconsistency in engineering solutions	Budget Estimate: Low Should be addressed through LDRP45
Valuation data for all CCC assets within the project areas - water, wastewater, stormwater, roading and community facilities There are gaps in the stormwater valuation data provided (recent assets) and no water, wastewater, roading or community facilities valuation data has been provided.	Benefit: Would be used in cost estimates for mitigation or realignment options in Stage 3 Risk: Assumptions mean inaccuracies	Budget Estimate: Low
Recent construction cost data No recent construction costs have been provided for stormwater pump stations or stopbanks.	Benefit: Reference for cost estimating Risk: Assumptions mean inaccuracies	Budget Estimate: Low
Policy on other utilities costs There is no information on CCC's policy on cost sharing for abandoning or replacing other utilities.	Needed in order to determine whether or not to include other utilities in Stage 3 cost estimates Risk: Under/over accounting	Budget Estimate: Low
Other utilities valuation data While information on existing other utilities is available through the SCIRT GIS, we do not have any information on the capital value of these assets.	Benefit: Would be used in cost estimates for mitigation or realignment options in Stage 3 Risk: Under/over accounting	Budget Estimate: Low

O&M costs for stormwater assets CCC stormwater O&M budgets provided are very high level and do not include a breakdown or unit cost.	Needed in order to carry out NPV including O&M as part of Stage 3.	Budget Estimate: Low

PART FIVE: GAP ANALYSIS SUMMARY RECOMMENDATIONS

15. Summary Recommendations

15.1 Gaps Recommended to be filled in Project Stage Two

Within the sections of this report, we have identified a number of gaps. These gaps have been collated into studies, and ordered into priorities below. Detailed methodologies and project briefs will be prepared on agreement with council.

Study Number	Gap Filling Studies Needed for Multi-Hazards Study with high level scopes.	Benefit if Addressed / Risk if not Addressed	Indicative Budget (1)	Already in Progress
1	**Flooding, Extreme Weather and Coastal Erosion/Inundation Coincidence Investigation** a) Historical review of previous floods and identifies coincidence with other hazard events. b) Assess the relationship between different types of storms and flooding. c) Analysis of extreme storm tide and wave environment. d) Evaluate Coincidence between storm surge, fluvial and pluvial flooding including the Ihutai/Avon-Heathcote Estuary and Styx. e) Joint Probability Analysis of extreme tide and wave environment within the estuary.	**Benefit:** These studies represent a significant information gaps that, if filled, would help inform us of the likelihood of coincidence and extent of exacerbation of fluvial and pluvial flooding in extreme weather and coastal erosion/inundation events. **Risk:** Joint probabilities of co-incidences not well known leading to high level of assumptions for multi-hazard analysis.	High	No
2	**Council Policy Implementation Options** a) Understand options for implementation of policy options.	**Benefit:** Stage 3 will include consideration of applying policy options and engineering mitigation options. Allows equal levels of definition for options comparison. **Risk:** Without understanding Council policy on retreat and property/land purchase, a number of assumptions will need to be made including triggers, timeframes and costs of retreat options.	High	No
3	**Detailed Information** a) Valuation data for all CCC assets within the project areas - water, wastewater, stormwater, roading and community facilities. b) Recent construction cost data. c) Policy on other utilities costs. d) Other utilities valuation data. e) O&M costs for stormwater assets.	**Benefit:** Reference for cost estimating. Data provided was high level and not detailed to particular asset tags. **Risk:** Under or over accounting, assumptions mean inaccuracies.	Low	N/A – To be completed by CCC.
4	**Level of Service definition** a) Define levels of service for stormwater and flood mitigation infrastructure. b) Define levels of service for groundwater management.	**Benefit:** Level of service needs to be defined before carrying out concept design for pump stations and stopbanks/flood walls in Stage 3. **Risk:** Inconsistency with	Low	a) Stormwater and Flood Mitigation b) Expected in LDRP45

Study Number	Gap Filling Studies Needed for Multi-Hazards Study with high level scopes.	Benefit if Addressed / Risk if not Addressed	Indicative Budget (1)	Already in Progress
		engineered solutions.		
5	**Coastal Erosion/Inundation with climate and sediment budget changes** a) Assess and identify changes in future coastal erosion and inundation extents with changes in climate b) Assess and identify changes in future coastal erosion and inundation extents with changes in sediment budgets.	**Benefit:** More robust coastal erosion and inundation prediction maps will inform decisions around flood management areas, and infrastructure design standards and locations, in Stage 3 of this project. **Risk:** Stage 3 options do not account for accurate level of risk posed by erosion to infrastructure in the coastal margin.	N/A Medium to high	a) Tonkin & Taylor project – Coastal Reassessment for climate change. b) No
6	**Vertical Land Displacement Lidar development** a) Develop vertical land displacement datasets in a range of return period and source future earthquake events. b) Identify the probability of different sourced earthquake events that causes geomorphological change that affects flood risk.	**Benefit:** If addressed a greater range of possible effects will be known for events that may be more probable than a repeat CES. **Risk:** If not addressed there could be challenge in terms of only using a low probability but high impact event.	Medium	a) LDRP110 & 45 for some study areas, but out of scope for other areas b) No
7	**Changes in Groundwater with a changing environment** a) Changes of extreme groundwater levels with sea level rise and rainfall changes. b) Accounting for future groundwater levels within climate change flood modelling.	**Benefit:** Benefit is a more relevant understanding of the impacts of climate change on groundwater levels and flood risk, as well as the variation of these impacts with climate change. **Risk:** Options considered do not appropriately consider and address groundwater change impacts.	Low	a) LDRP45 b) No
9	**Tsunami Modelling of frequent events** a) Modelling of inundation levels for 100 and 500 year return period events, height and wave return period and mapping. b) Identify maximum credible amplitude and inundation from locally generated tsunamis, scour impact investigation, and combined sea level rise and tsunami inundation mapping.	**Benefit:** Remove uncertainty on the level of risk from such events. **Risk:** Uncertainty remains, so impacts and risks may be underestimated.	High	No
10	**Liquefaction risk to non-residential land** a) Assessment and mapping of liquefaction risk from non-residential land. b) Convert liquefaction to groundwater subsidence and groundwater	**Benefit:** Greater knowledge of liquefaction risk across the study area if addressed. **Risk:** Incomplete spatial dataset to identify risk to sites not presently developed for residential use.	Med	a) Yes – In T&T Liquefaction Study b) Yes – Link between LDRP45 and T&T Liquefaction Study
Notes: (1) Indicative Budget levels: (Low <$20k, Med $20-$50k, High >$50k)				

15.2 Stage 3 Recommendations

At present we foresee Stage 3 largely being consistent with as it was scoped but make the following recommendations:

- Adaptive planning must be at the forefront of this project.
- It is recommended that Stage 3 of the project not be started until the above studies have been completed to allow the spatial co-location to be updated. Hence it is recommended that Stage 3 of the study change from a “programme orientated” study to a “milestone orientated” study.
- Before commencing Stage 3 of the study, the spatial co-location maps (Appendix B/2 and B/3) will need to be updated to include the results from the following single hazard studies currently underway and anticipated to be completed before Stage 3 commences.
  - Further Coastal Erosion and Coastal Inundation – Tonkin &Taylor Reassessment:
  - Liquefaction Mapping – Tonkin & Taylor city wide investigation and mapping project.
  - Effect of Earthquakes on Groundwater Investigation (LDRP45 project) – Aqualink and Beca.
  - City Wide Flood modelling (LDRP44 project).
- The spatial co-location update is required as this could have significant influence on the options chosen to be assessed in stage 3, and therefore preconceived views on options cannot be made ahead of this stage and must acknowledge previous work undertaken and not seek to redo already assessed options unless the hazard science changes the outcome.
- Retreat should be developed as one option for the city; not by areas.

15.3 Wider Recommendations

The objective of LDRP97 has been agreed with Council as:

Develop <u>floodplain management plans</u> for the study area, involving developing a range of sustainable and resilient flood mitigation options including engineering, planning and policy responses.

In the context of this project there is special reference to taking into account the influences of other natural hazards and long term changes (e.g. climate change) on the magnitude, frequency and extent of the flooding, as well as on the sustainability and resilience of the mitigation options.

The LDRP97 project charter states three related aims of the project as:

f) What will be the cost of other interventions that may be required to ensure feasibility of occupation of the land if floodplain defences are installed? What risks might the land still be subject to and what potential damages are associated with these risks being realised? (Section 1.1 item 5)

g) What are the costs of each hazard management scenario and damages associated with residual risks and unmitigated hazards? (Section 1.3 item 3)

h) What is the cost to effectively manage all future hazards (up to the point where land can still be feasibly occupied) for comparison to policy options? (Section 1.3 item 8)

Answering these questions suggests the following tasks are required:

1. **Estimate economic and other metrics for the consequences of all (non-flood) hazards.** For flooding, Council calculates the number of floor levels at risk and the economic cost of damage. Comparable metrics would be required for other hazards so that mitigations can be justified. Flood economics in Christchurch are based in part on data from RiskScape, which also provides a framework for understanding the impact of other natural hazards (tsunami, earthquakes, wind and volcanic

hazards). Investigation is required into how readily RiskScape or other data can be used to estimate the economic consequences of each hazard.

2. **Develop mitigation options and costs for all (non-flood) hazards.** For each natural hazard which a parcel of land is subject to, estimate the cost of engineering works or policy responses to mitigate the hazard so that the land can be occupied. Many areas of the city are at risk from multiple hazards which may require different responses (e.g. earthquake resilience may require improved foundations whereas protection from coastal erosion may require sea walls). This in turn requires definition of a level of service for each hazard.

3. **Comparison of responses for flooding and other hazards for all areas.** Only when the different responses can be compared will the study of multi-hazards suggest anything different (or anything at all) should be done for flooding.

These are vital tasks for Christchurch to become resilient to all natural hazards and to make informed decisions about future land use. However, undertaking these tasks goes beyond the current scope of LDRP97 which is focussed in Stage 3 on developing flood management plans. Our understanding is that these tasks are not currently being addressed by any anticipated work. Therefore, we consider these tasks as gaps which, if filled, will allow Council to answer the wider questions posed beyond the LDRP97 study.

Appendix A. Individual Hazard Maps

A1: Known Flood Risk: CCC Flood Management Areas and High Flood Hazard Management Areas

A2: Coastal Erosion

A3: Coastal Inundation

A4: Far Field Tsunami

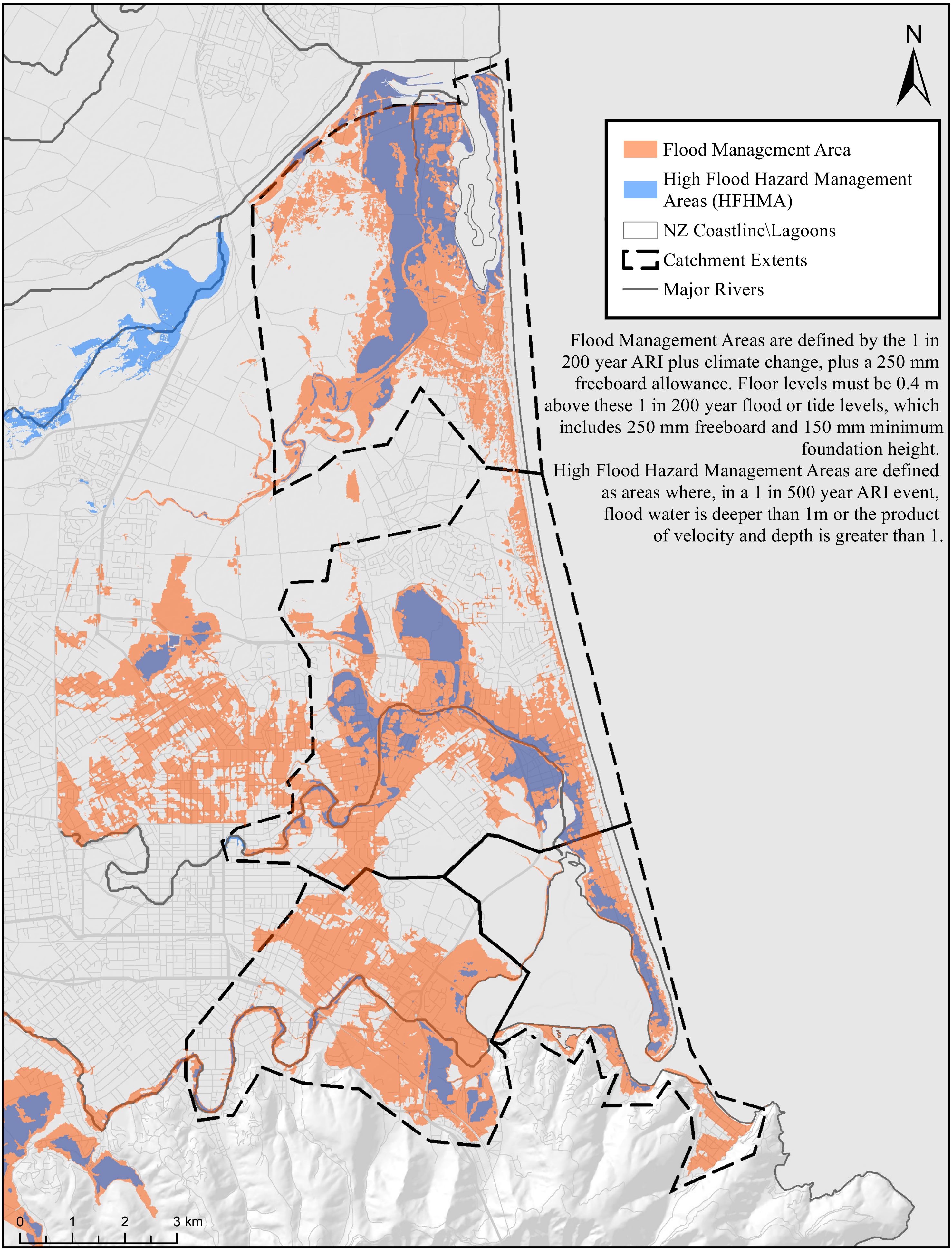
A5: Near Field Tsunami

A6a and A6b: Vertical Displacement

A7a and A7b: Liquefaction

A8: Groundwater

A9: Recorded Mass Movements



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Date: 5/05/2017

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LDRP 97 Map A1: Known Flood Risk

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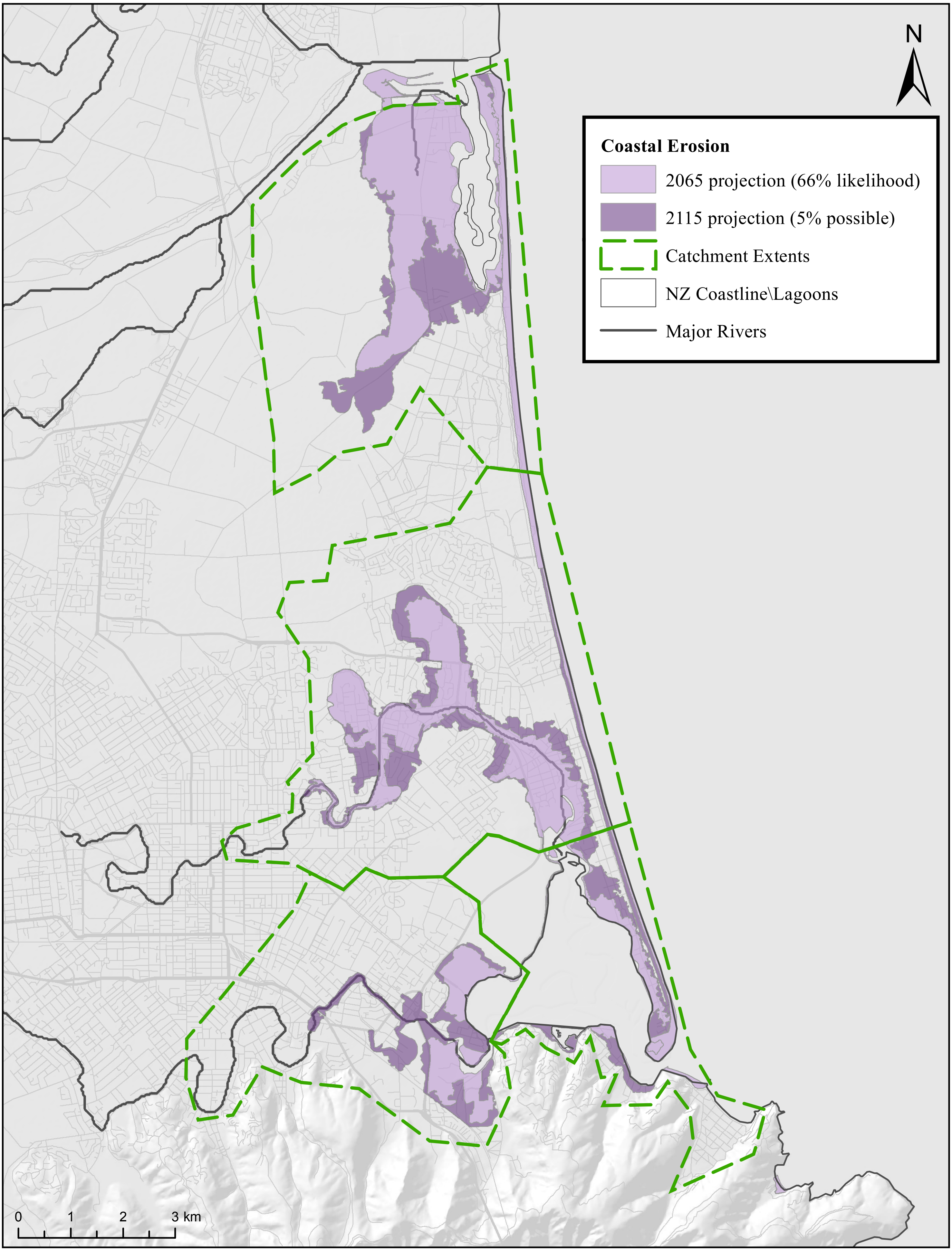

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Date: 5/05/2017

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LDRP 97 Map A2: Coastal Erosion

Tonkin & Taylor Ltd (2015) Coastal hazards assessment: Stage 2 Report (851847.001)

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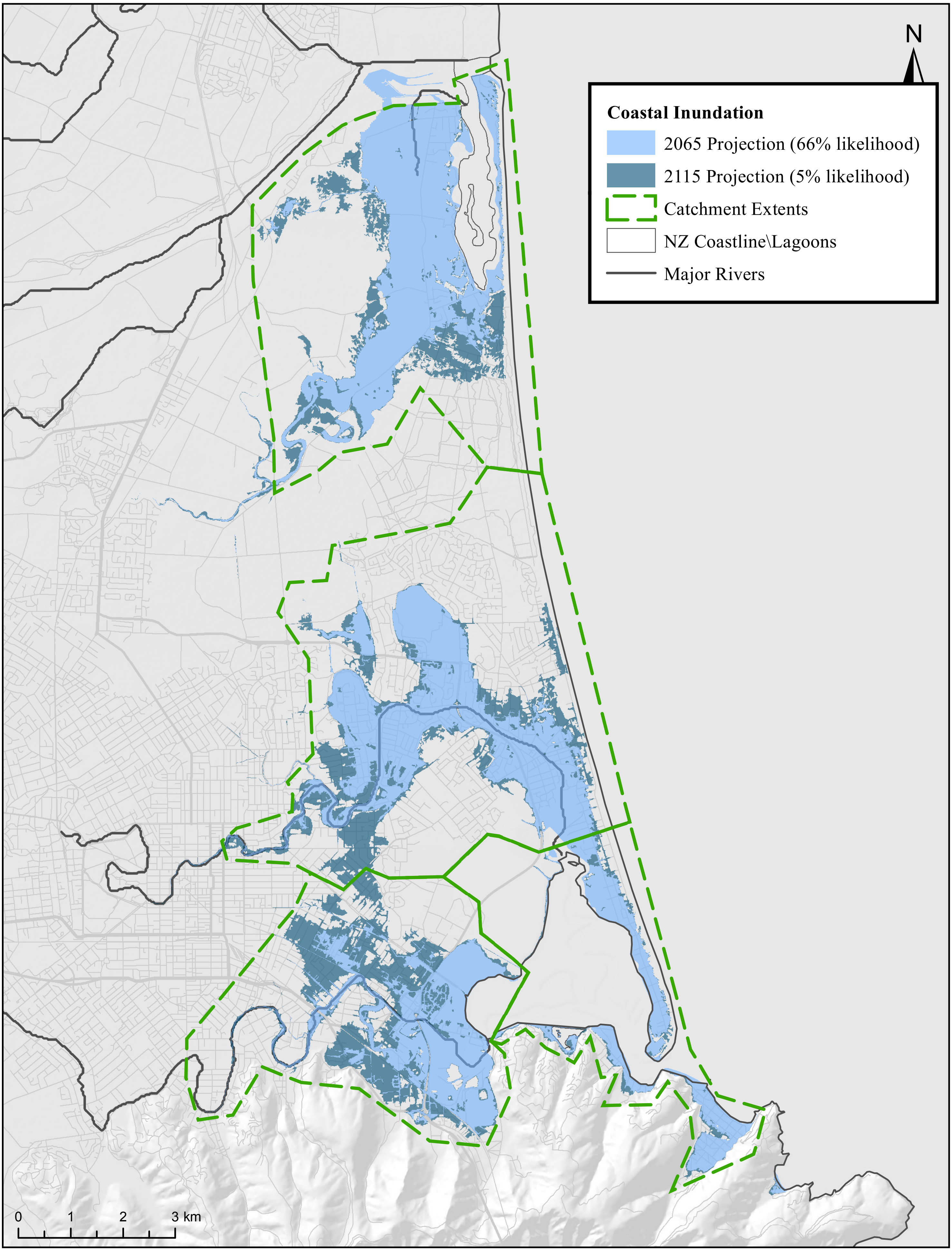

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Date: 5/05/2017

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LDRP 97 Map A3: Coastal Inundation

Tonkin & Taylor Ltd (2015) Coastal hazards assessment: Stage 2 Report (851847.001)

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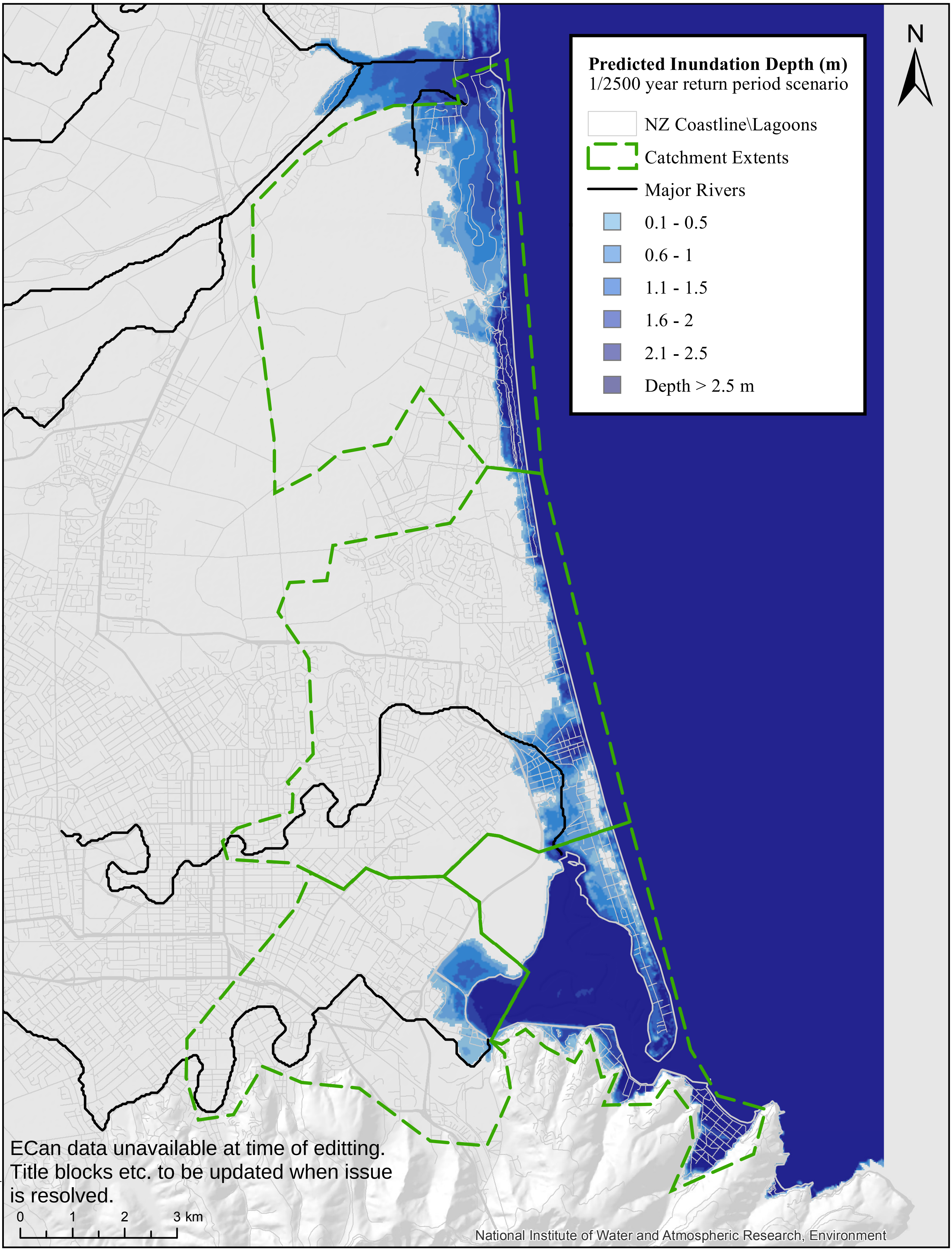

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Date: 29/03/2017

Land Drainage Recovery Programme

LDRP 97 Map 1a: Tsunami Inundation - Far Field Source

Lane, E., Kohout, A., Chiaverini, A., Jade, A., & Canterbury, E. (2014). Updated inundation modelling in Canterbury from a South American Tsunami. Environment Canterbury report number R14/78. Christchurch, New Zealand.

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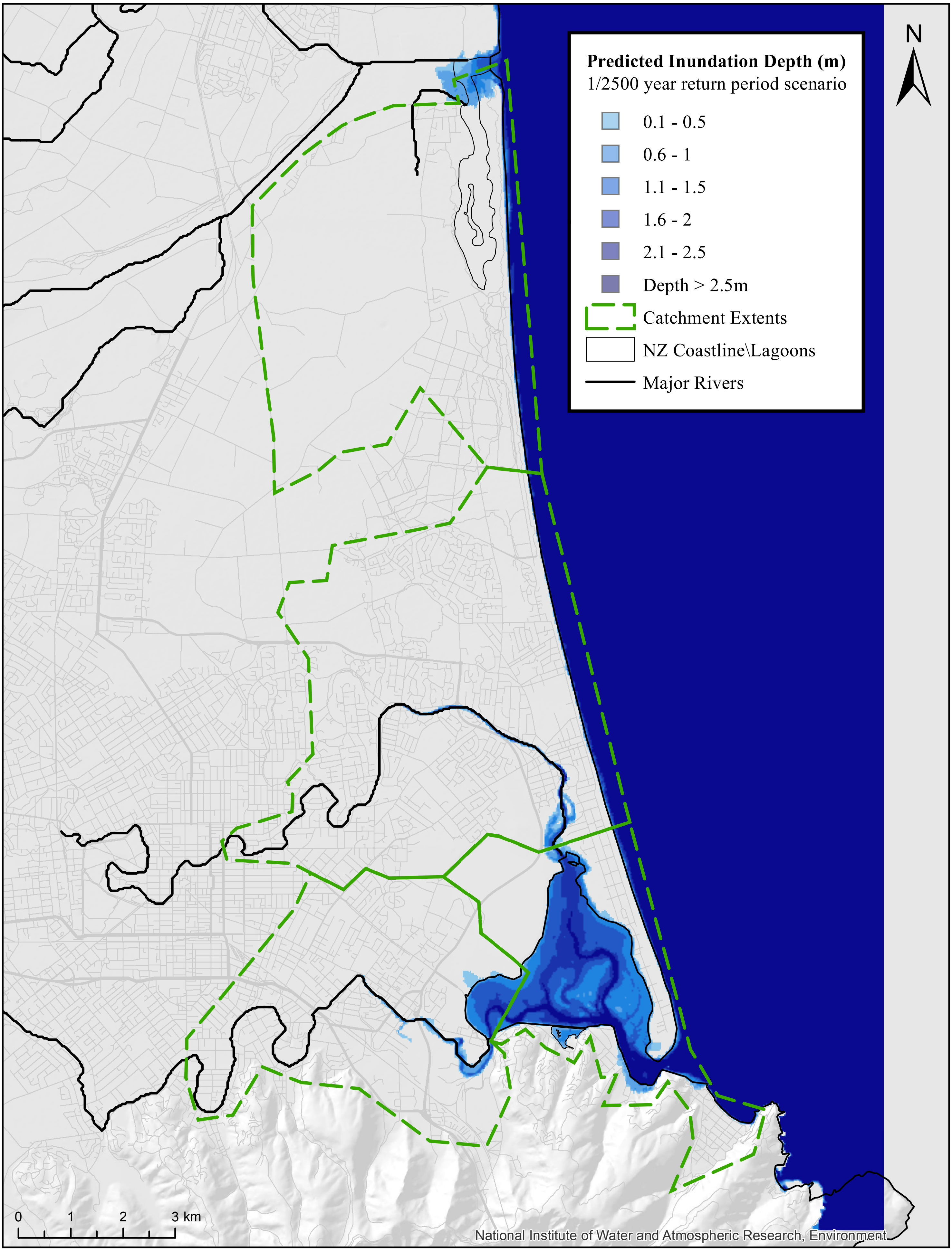

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Date: 5/05/2017

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LDRP 97 Map A5: Tsunami Inundation - Regional (Wairarapa and Hikurangi) Sources

Kohout, A., Lane, E., Arnold, J., & Sykes, J. (2015). Hikurangi Subduction Zone and Wairarapa Fault tsunami modelling for the Canterbury coast. Environment Canterbury report number R15/130. Christchurch, New Zealand.

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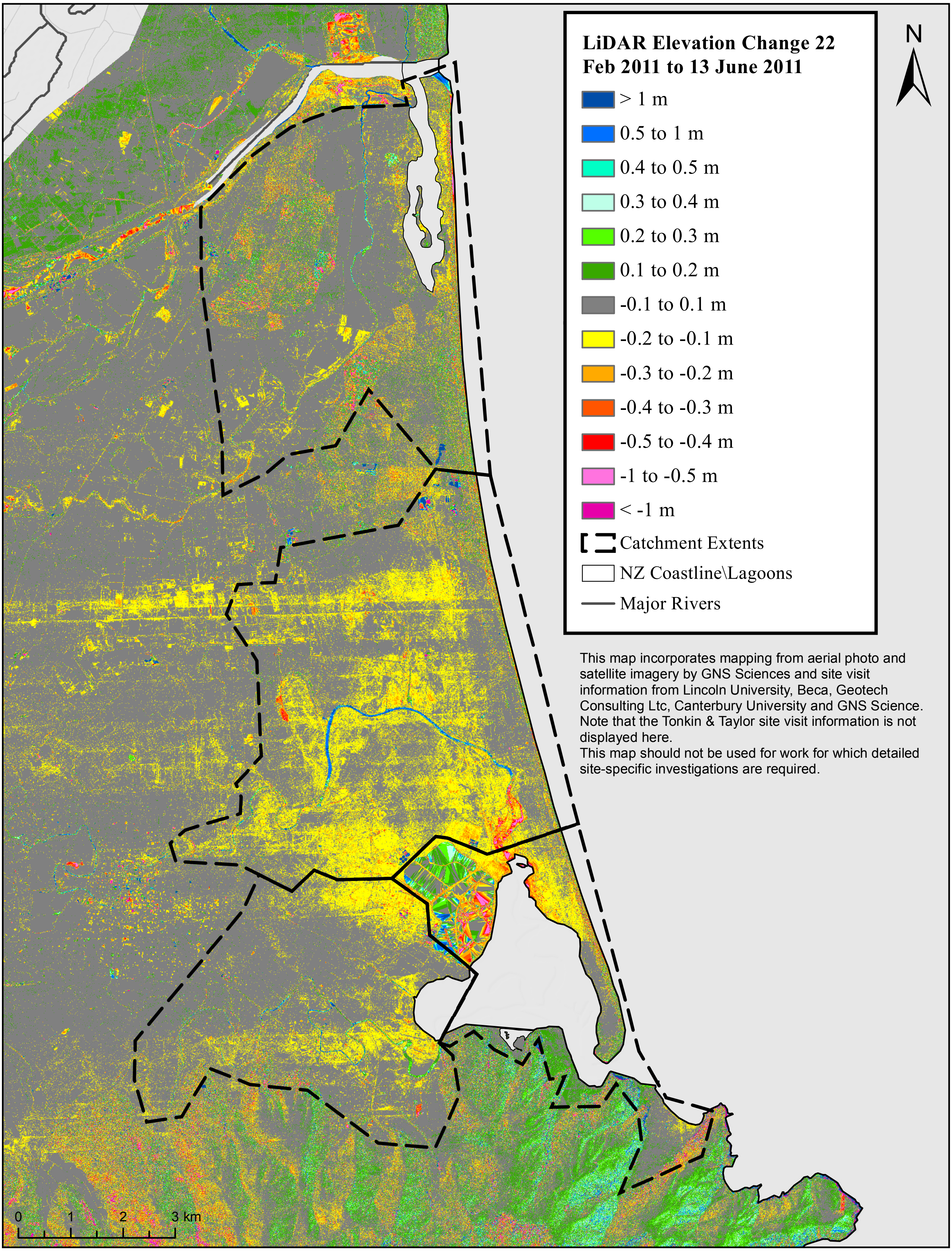

This map incorporates mapping from aerial photo and satellite imagery by GNS Sciences and site visit information from Lincoln University, Beca, Geotech Consulting Ltc, Canterbury University and GNS Science. Note that the Tonkin & Taylor site visit information is not displayed here.
This map should not be used for work for which detailed site-specific investigations are required.

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Date: 12/05/2017

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LDRP 97 Map A6a: Earthquake EQC Vertical Ground Displacements, 22 Feb 2011 to 13 June 2011

Canterbury Geotechnical Database (2012) "Vertical Ground Surface Movements", Map Layer CGD0600 - 23 July 2012

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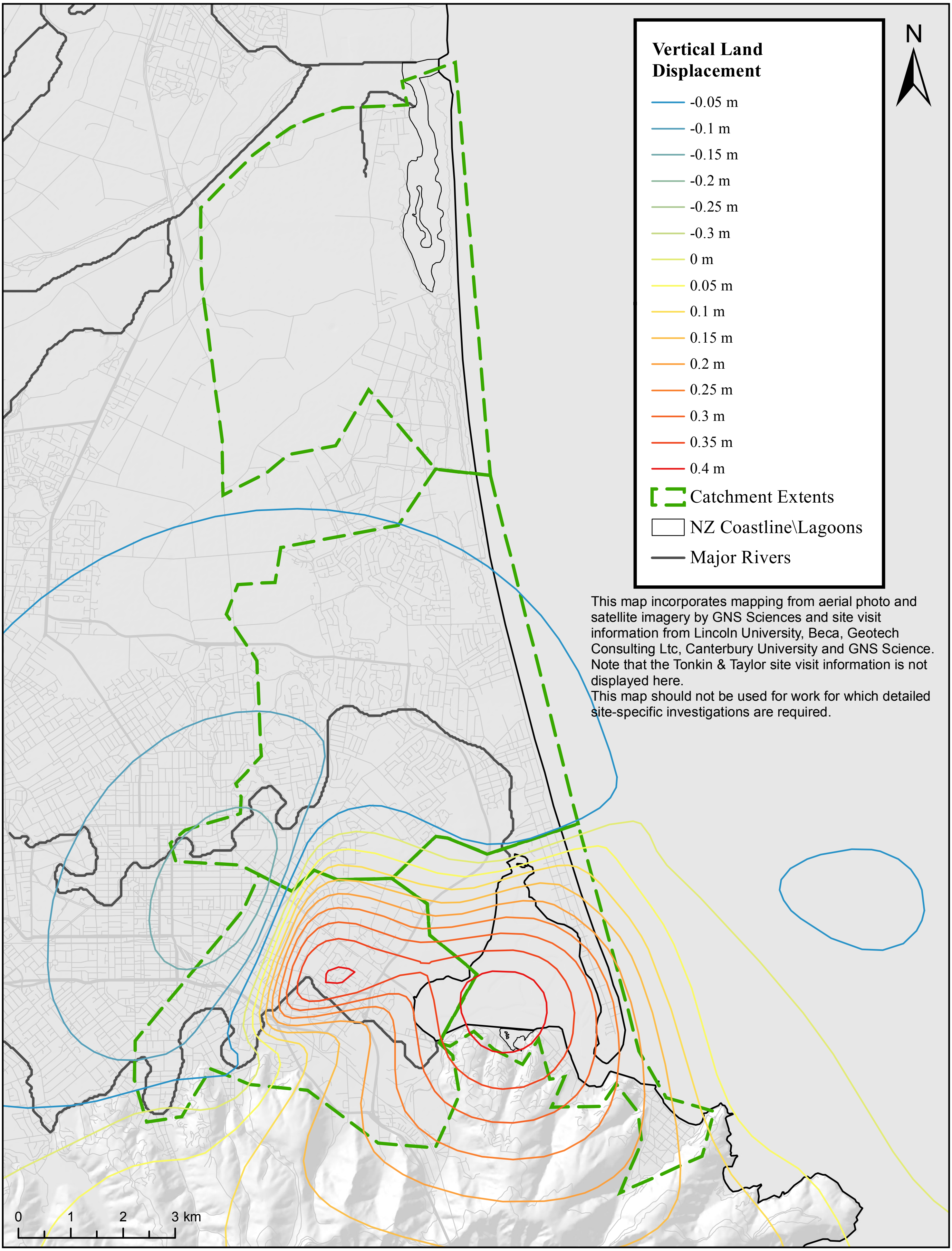

This map incorporates mapping from aerial photo and satellite imagery by GNS Sciences and site visit information from Lincoln University, Beca, Geotech Consulting Ltd, Canterbury University and GNS Science. Note that the Tonkin & Taylor site visit information is not displayed here.
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Date: 12/05/2017

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LDRP 97 Map A6b: Earthquake EQC Vertical Ground Displacements, 4 Sept 2010 to 13 June 2011

Canterbury Geotechnical Database (2012) "Vertical Ground Surface Movements", Map Layer CGD0600 - 23 July 2012

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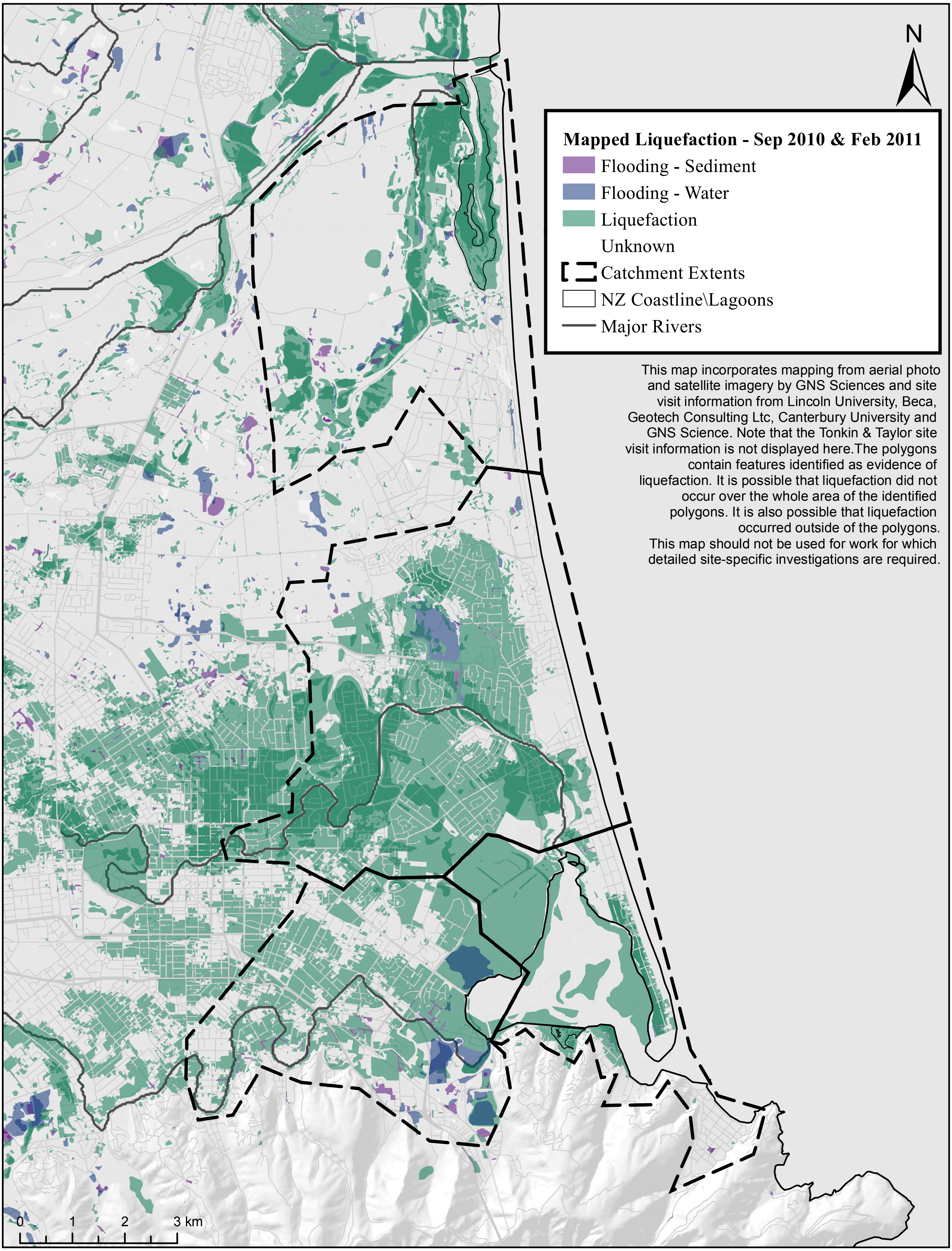

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LDRP 97 Map A7a: Liquefaction Susceptability, Sep-2010 and Feb-2011 Liquefaction Occurences

Brackley (2012), Review of liquefaction hazard information in eastern Canterbury, including Christchurch City and parts of Selwyn, Waimakariri and Hurunui Districts. Environment Canterbury report R12/83.

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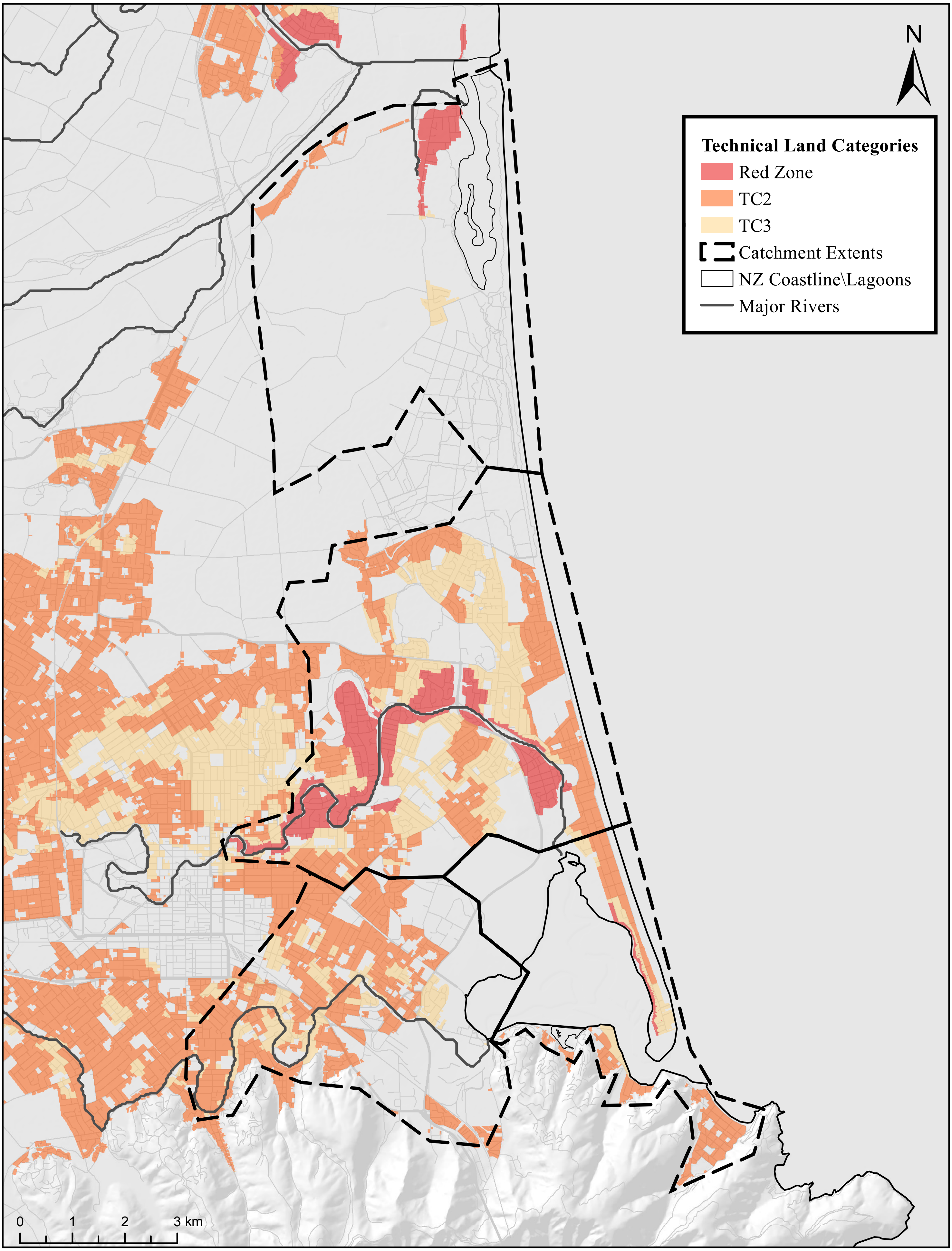

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Date: 12/05/2017

Land Drainage Recovery Programme

LDRP 97 Map A7b: Liquefaction Susceptibility, Technical Land Categories

Brackley (2012), Review of liquefaction hazard information in eastern Canterbury, including Christchurch City and parts of Selwyn, Waimakariri and Hurunui Districts. Environment Canterbury report R12/83.

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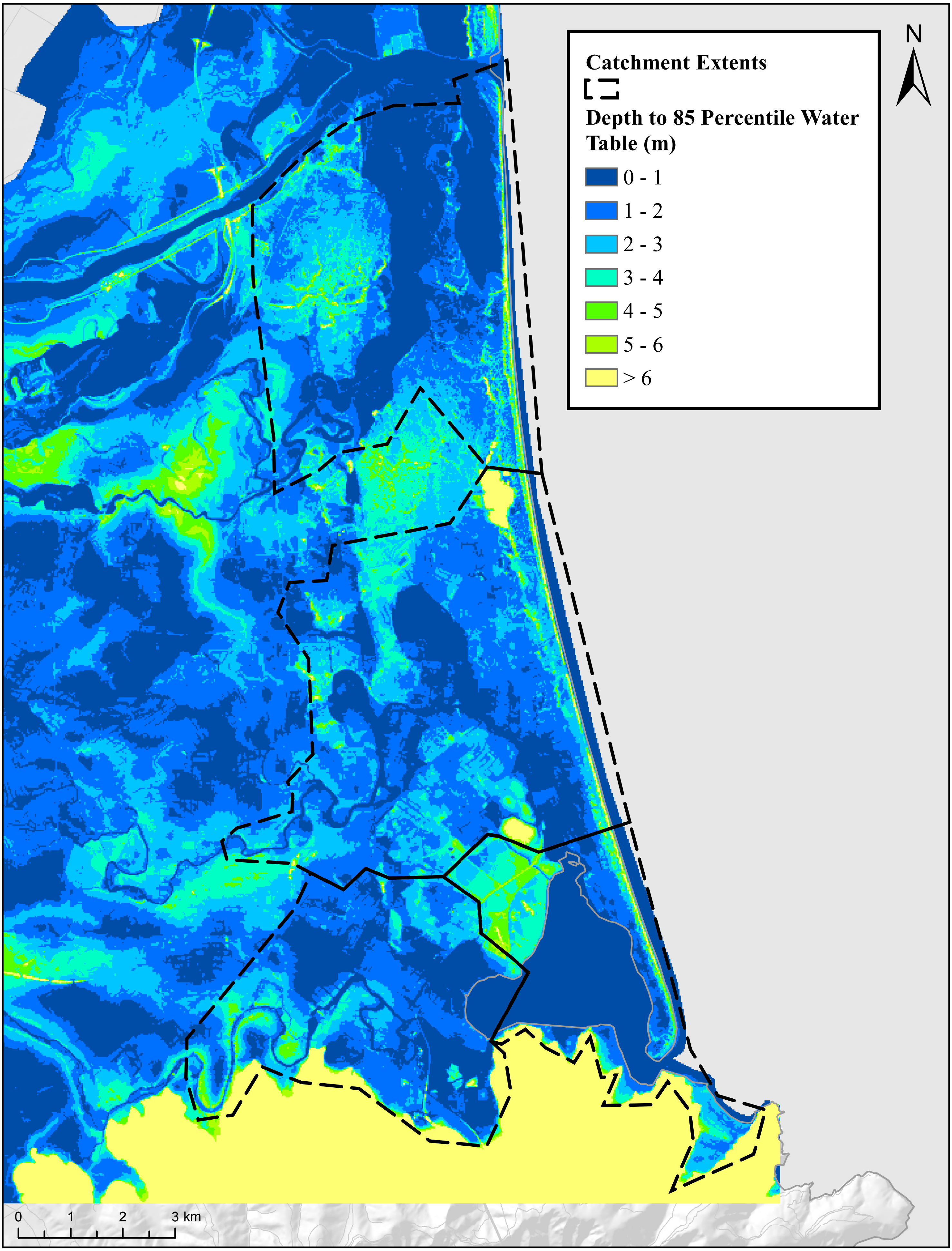

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Date: 5/05/2017

Land Drainage Recovery Programme

LDRP 97 Map A8: Depth to Groundwater Table

van Ballegooy, S.; Cox, S. C.; Thurlow, C.; Rutter, H. K.; Reynolds, T.; Harrington, G.; Fraser, J.; Smith, T. (2014) Median water table elevation in Christchurch and surrounding area after the 4 September 2010 Darfield Earthquake: Version 2, GNS Science Report 2014/18.

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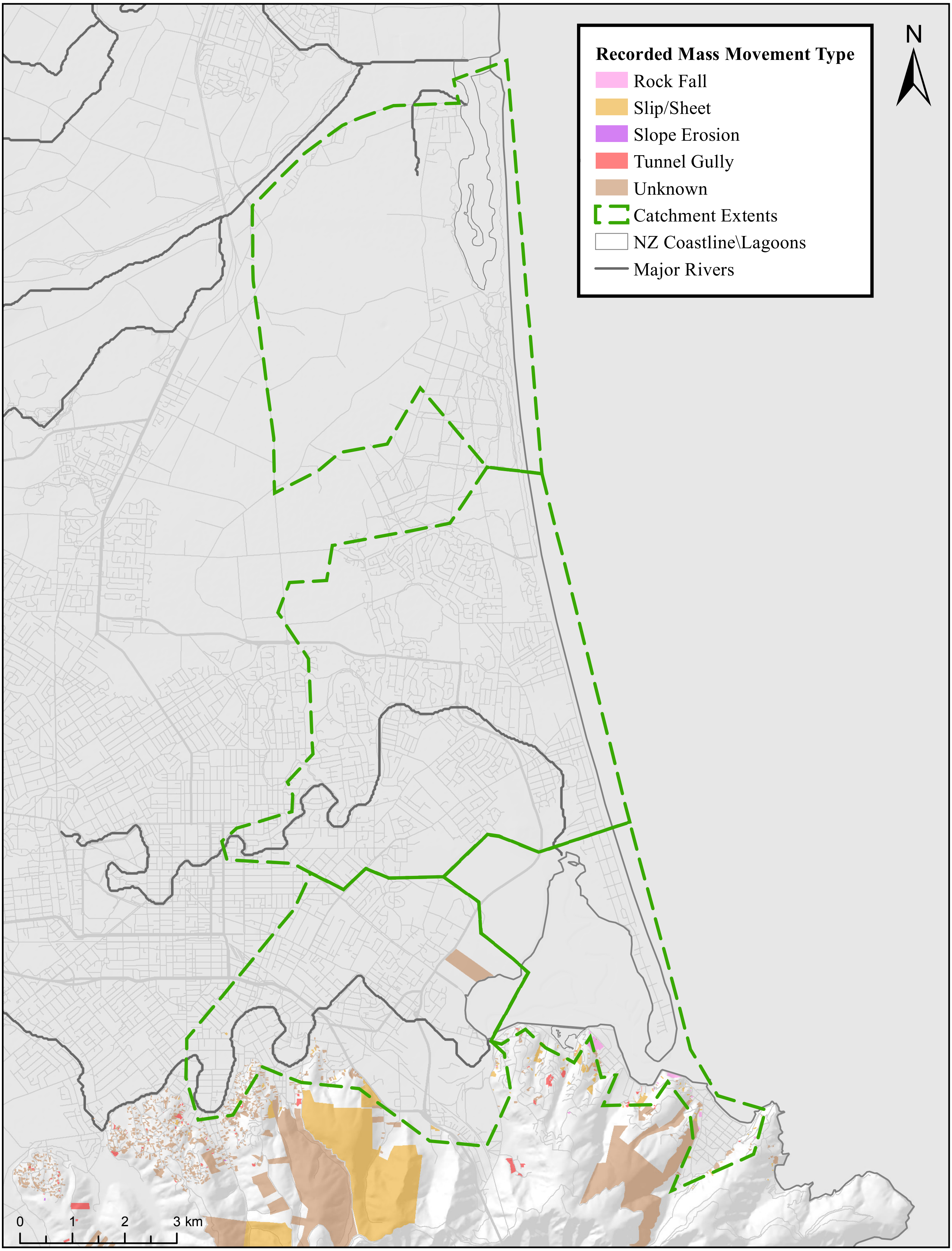

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Date: 5/05/2017

Land Drainage Recovery Programme

LDRP 97 Map A9: Mass Movements (Recorded)

LWRP High Erosion Risk Area, Environment Canterbury (2015) https://data.canterburymaps.govt.nz/layer/7559/; GroundCharacteristics Recorded Erosion & vwErosion, CCC Web Feature Service (WFS)

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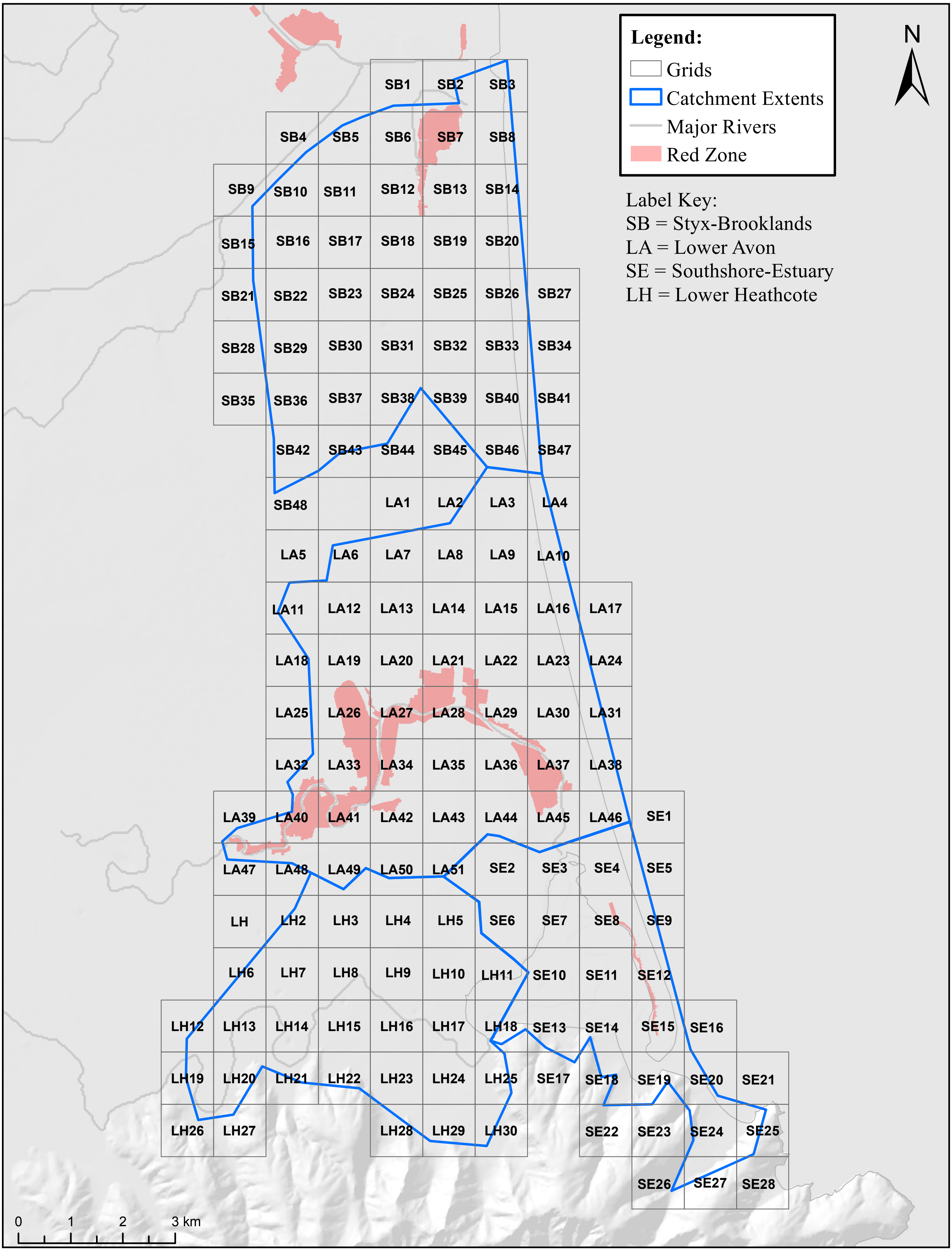
Appendix B. Hazard Co-location Maps

B1: Grid Cells for Co-location Analysis

B2: First Pass Spatial Co-location Map

B3B3: Second Pass Spatial Co-location Intensity Map



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Date: 12/05/2017

Land Drainage Recovery Programme

LDRP 97 Map B1: Spatial Co-location of Multiple Hazards Summary - Grids

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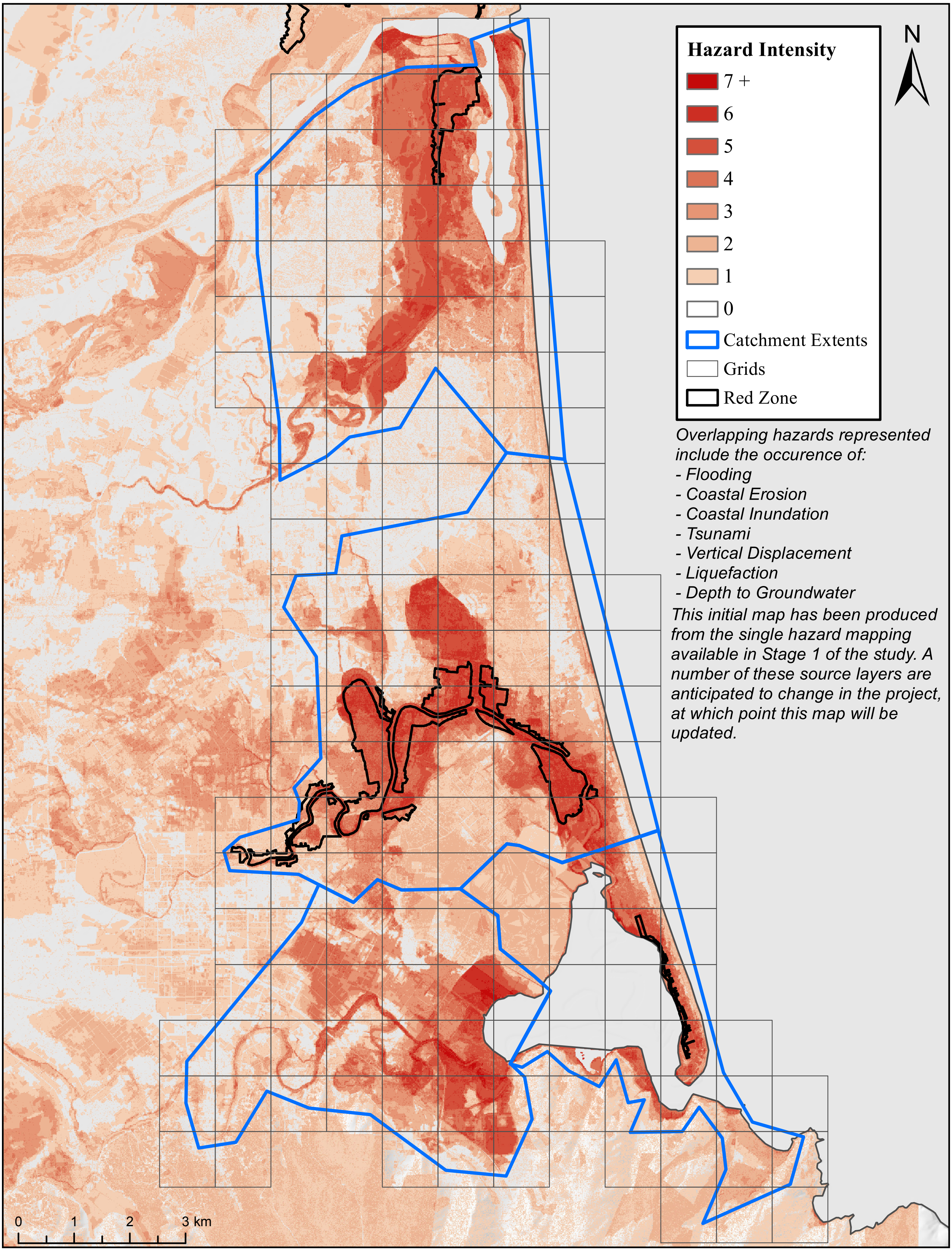

Date: 12/05/2017

Land Drainage Recovery Programme

LDRP97 Map B2: Spatial Co-location of Multiple Hazards

Summary - First Pass Multiple Hazard Coverage

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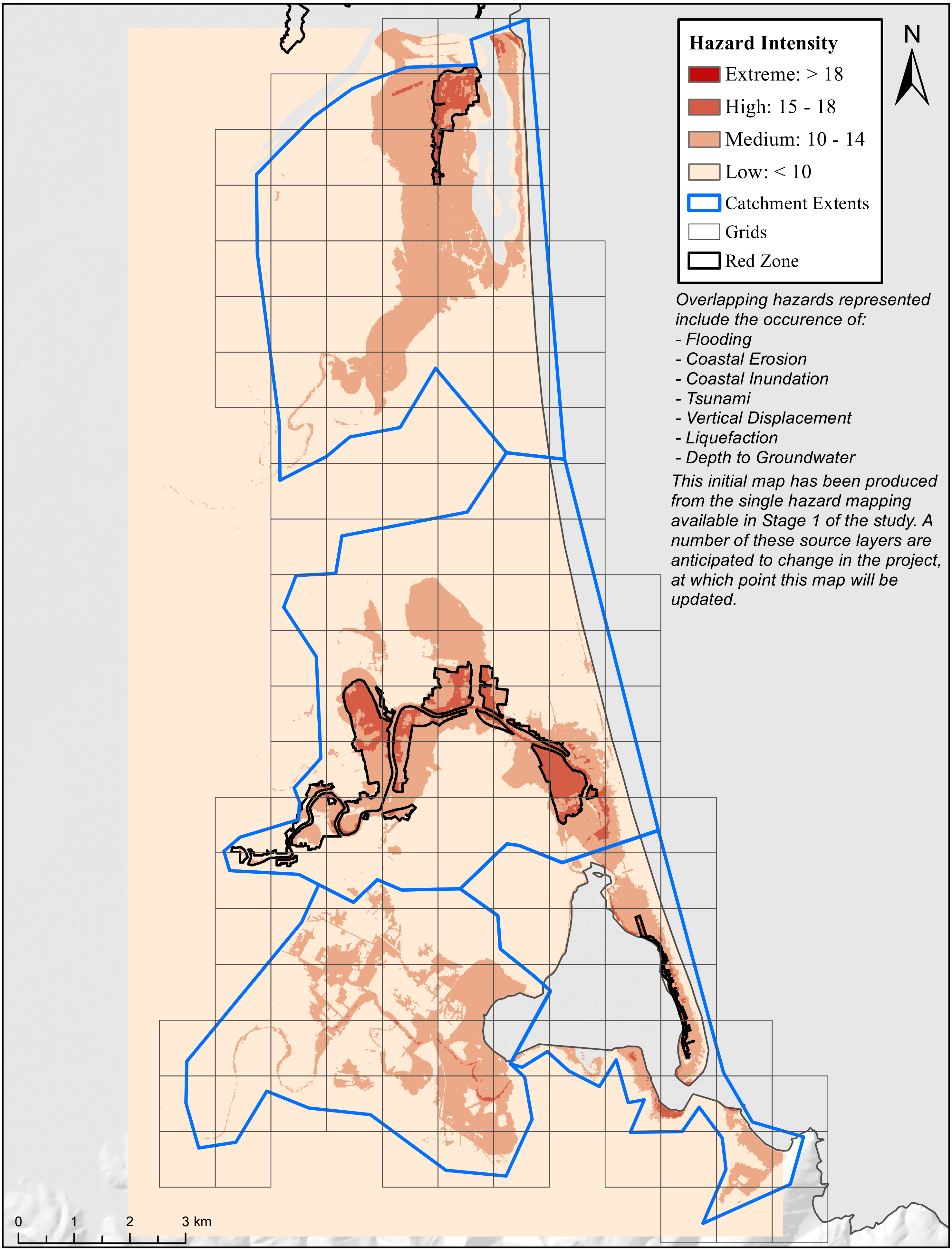

Overlapping hazards represented include the occurence of:

- *Flooding*
- *Coastal Erosion*
- *Coastal Inundation*
- *Tsunami*
- *Vertical Displacement*
- *Liquefaction*
- *Depth to Groundwater*

This initial map has been produced from the single hazard mapping available in Stage 1 of the study. A number of these source layers are anticipated to change in the project, at which point this map will be updated.

C:\Users\clward\Documents\Water Mapping\Odd Jobs\9b - Summary Multi Coverage.mxd

Date: 12/05/2017

Land Drainage Recovery Programme

LDRP97 Map B3: Spatial Co-location of Multiple Hazards
Summary - Second Pass Multiple Hazard Coverage

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Appendix C. Additional Fluvial and Pluvial Flooding Data

There are currently two different classifications used to broadly classify synoptic weather in New Zealand. The most established of these are the Kidson Types, where synoptic weather patterns have been broadly divided into three groups and twelve daily weather classes from NCEP/NCAR reanalysis data (Kidson, 1994a, 1994b, 2000). The data-set currently runs from January 1958 to February 2017 and is updated regularly by Dr James Renwick at NIWA. Details of the classification methodology can be found in Kidson (2000) and Renwick (2011).

Kidson weather groups and types are shown in Error! Reference source not found., the mean 1000 Pa heights associated with the 12 daily synoptic classes are shown in Figure 0-1. The 'Trough' group includes four classes when there are troughs over and to the west of the country, the 'Zonal' group is typified by intense high pressure systems centred north of 40ºS and strong westerly winds to the south of the country, and the 'Blocking' group have high pressure centres to the south and east of New Zealand.

Table 15-1 New Zealand synoptic-scale weather groups and types (adapted from Kidson, 2000)

Group	Type	Description
TROUGH	T	Trough
	SW	South-westerly airflow
	TNW	Trough in North-westerly airflow
	TSW	Trough in South-westerly airflow
ZONAL	H	High pressure over the country
	HNW	High pressure to the north-west of New Zealand
	W	High pressure to the north, with westerly airflow over New Zealand
BLOCKING	HSE	High pressure to the south-east of New Zealand
	HE	High pressure to the east of New Zealand
	NE	North-easterly airflow
	HW	High pressure to the west of New Zealand
	R	Ridge over southern New Zealand

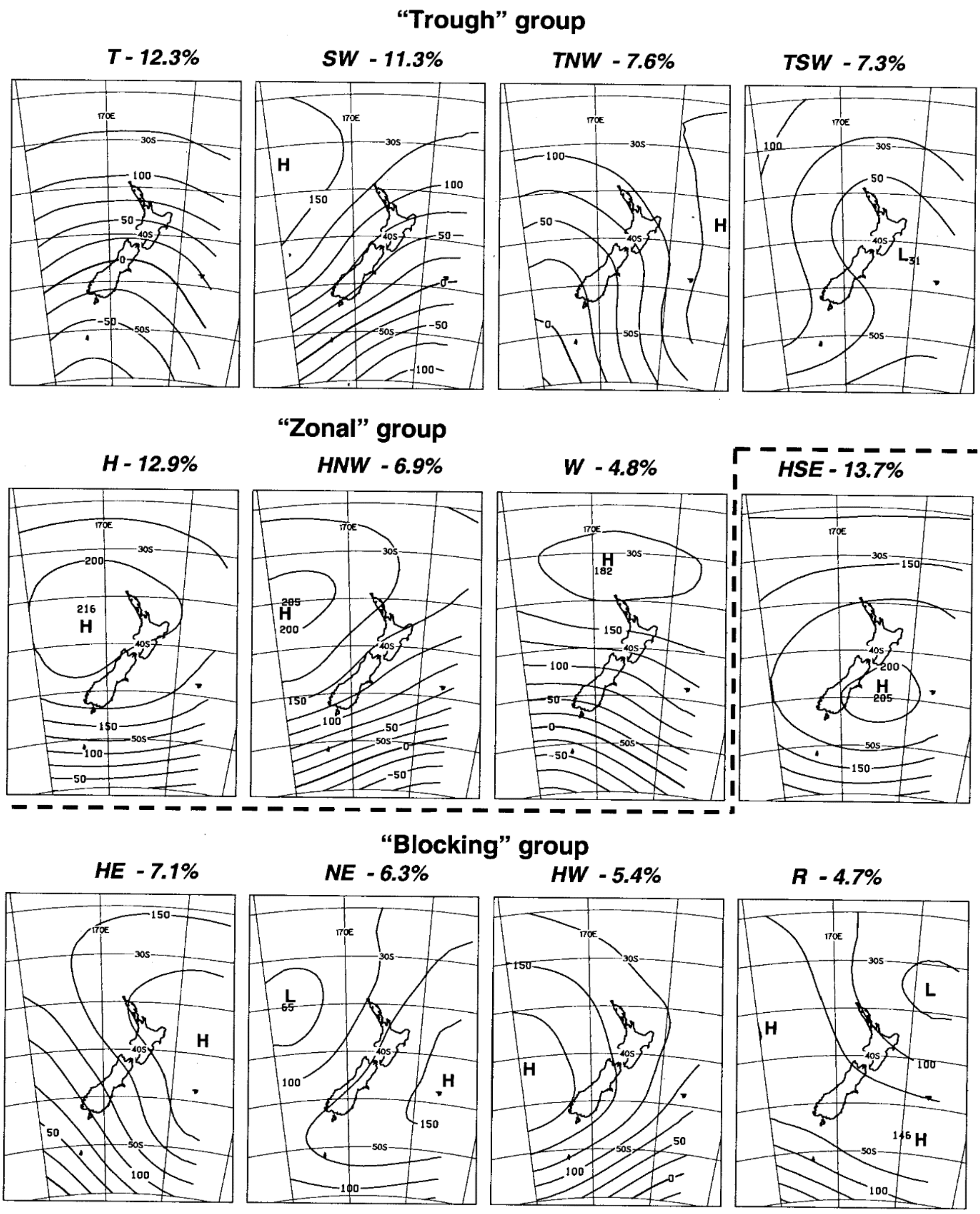

Figure 15-1 Mean 1000 hPa heights associated with Kidson synoptic types and groups (Kidson, 2000)

Appendix D. Previous Engineering Studies

The existing engineering studies and available information on existing engineering infrastructure have been provided by CCC and are summarised below.

Avon River

- Temporary Stopbanks O&M Manual
- River and Tidal Flood Protection Avon Stage 1 Draft
- LDRP62 & 97 Avon-Heathcote Tidal Barrier Pre-Feasibility Study, Peer Review & Cost Estimate Peer Review
- River Mouth Pump Stations Memo
- Knights Drain Issues and Options
- LDRP2 and 507 Temporary Stopbanks Management Options Report
- Avon River Stopbanks Refinement Report
- Avon SMP Blueprint Report
- Ōtākaro Avon Stormwater Management Plan Technical Reports, including:
  - Catchment Flood Modelling
  - Contaminant Load Modelling
  - Ecological Survey
  - Groundwater Quality
  - Groundwater Quantity
  - Springs and Wetlands
  - Cultural Health of the Estuary 2007 and 2012
  - Surface Water Quality 2013 and 2014
  - Wet Weather Monitoring
- LDRP19 Travis Wetland Outfalls - Issues and Options Report

Heathcote River

- Woolston Barrage O&M manual
- River and Tidal Flood Protection Heathcote Stage 1 Draft
- LDRP62 & 97 Avon-Heathcote Tidal Barrier Pre-Feasibility Study, Peer Review & Cost Estimate Peer Review
- River Mouth Pump Stations Memo
- LDRP88 Upper Heathcote Storage Options Study
- LDRP35 City Outfall Drain
- LDRP501 Bells Creek Preliminary Design & Stage 2 Issues, Options and Concept Report
- LDRP12 Steamwharf Stream Issues and Options Report & Model Status Report

Lower Styx River

- River and Tidal Flood Protection Styx Stage 1 Draft
- Styx SMP Blueprint Report
- LDRP09 Styx Operational Water Levels

Southshore & Estuary

- River and Tidal Flood Protection Estuary Stage 1 Draft
- LDRP62 & 97 Avon-Heathcote Tidal Barrier Pre-Feasibility Study, Peer Review & Cost Estimate Peer Review
- LDRP111 South New Brighton Floodplain Management Options - Technical Issues and Options Report

General/All areas

- LDRP7 Options and Guidelines for Outfall Structures and Open Channels
- LDRP500 Stormwater Infrastructure Economic Model
- Value of Lifeline Seismic Risk Mitigation in Christchurch (very limited stormwater/flood specific information)
- Performance of Critical Lifeline Infrastructure in Christchurch City through the 2010-2011 Canterbury EQ (no stormwater/flood specific information)
- CCC stormwater valuation data and guidance notes
- CCC stormwater O&M budgets

In addition, a number of other LDRP projects and other projects are underway which will provide information for this project, these include:

- LDRP45 Effects of Earthquake on Groundwater Levels (Aqualinc)
- LDRP44 City Wide Flood Model (GHD/Aecom)
- LDRP106 Cost Models
- LDRP110 Heathcote Management Strategies (Jacobs)
- Styx River and Tidal Flood Protection Project
- CCC Liquefaction Study (Tonkin & Taylor)

Appendix E. Engineering Review Documents

Objectives and Policies, Chapter 11-Natural Hazards

Objectives

11.2.1 Avoid new subdivision, use and development of land that increases risks associated with natural hazards

New subdivision, use and development of land which increases the risk of natural hazards to people, property and infrastructure is avoided or, where avoidance is not possible, mitigation measures minimise such risks.

11.2.2 Adverse effects from hazard mitigation are avoided or mitigated

Adverse effects on people, property, infrastructure and the environment resulting from methods used to manage natural hazards are avoided or, where avoidance is not possible, mitigated.

11.2.3 Climate change and natural hazards

The effects of climate change, and its influence on sea levels and the frequency and severity of natural hazards are recognised and provided for.

11.2.4 Effective integration of the management of, and preparedness for, natural hazards

The level of cooperation between agencies and organisations necessary to achieve integrated management of Canterbury's natural hazards, and preparedness for natural hazards is maintained or enhanced.

Policies

11.3.1 Avoidance of inappropriate development in high hazard areas*

To avoid new subdivision, use and development (except as provided for in Policy 11.3.4) of land in high hazard areas*, unless the subdivision, use or development:

1. is not likely to result in loss of life or serious injuries in the event of a natural hazard occurrence; and

2. is not likely to suffer significant damage or loss in the event of a natural hazard occurrence; and

3. is not likely to require new or upgraded hazard mitigation works to mitigate or avoid the natural hazard; and

4. is not likely to exacerbate the effects of the natural hazard; or

5. Outside of greater Christchurch, is proposed to be located in an area zoned or identified in a district plan for urban residential, industrial or commercial use, at the date of notification of the CRPS, in which case the effects of the natural hazard must be mitigated; or

6. Within greater Christchurch, is proposed to be located in an area zoned in a district plan for urban residential, industrial or commercial use, or identified as a "Greenfield Priority Area" on Map A of

Chapter 6, both at the date the Land Use Recovery Plan was notified in the Gazette, in which case the effects of the natural hazard must be avoided or appropriately mitigated; or

7. Within greater Christchurch, relates to the maintenance and/or upgrading of existing critical or significant infrastructure.

**"High hazard areas" are:*

1. flood hazard areas subject to inundation events where the water depth (metres) x velocity (metres per second) is greater than or equal to 1, or where depths are greater than 1 metre, in a 0.2% AEP flood event;

2. land outside of greater Christchurch subject to coastal erosion over the next 100 years; and

3. land within greater Christchurch likely to be subject to coastal erosion including the cumulative effects of sea level rise over the next 100 years. This includes (but is not limited to) the land located within Hazard Zones 1 and 2 shown on Maps in Appendix 5 of this Regional Policy Statement that have been determined in accordance with Appendix 6; and

4. land subject to sea water inundation (excluding tsunami) over the next 100 years. This includes (but is not limited to) the land located within the sea water inundation zone boundary shown on Maps in Appendix 5 of this Regional Policy Statement.

When determining high hazard areas, projections on the effects of climate change will be taken into account.

11.3.2 Avoid development in areas subject to inundation

In areas not subject to Policy 11.3.1 that are subject to inundation by a 0.5% AEP flood event; any new subdivision, use and development (excluding critical infrastructure) shall be avoided unless there is no increased risk to life, and the subdivision, use or development:

1. is of a type that is not likely to suffer material damage in an inundation event; or

2. is ancillary or incidental to the main development; or

3. meets all of the following criteria:

(a) new buildings have an appropriate floor level above the 0.5% AEP design flood level; and

(b) hazardous substances will not be inundated during a 0.5% AEP flood event;

provided that a higher standard of management of inundation hazard events may be adopted where local catchment conditions warrant (as determined by a cost/benefit assessment).

When determining areas subject to inundation, climate change projections including sea level rise are to be taken into account.

11.3.3 Earthquake hazards

New subdivision, use and development of land on or close to an active earthquake fault trace, or in areas susceptible to liquefaction and lateral spreading, shall be managed in order to avoid or mitigate the adverse effects of fault rupture, liquefaction and lateral spreading.

11.3.4 Critical infrastructure

New critical infrastructure will be located outside high hazard areas unless there is no reasonable alternative. In relation to all areas, critical infrastructure must be designed to maintain, as far as practicable, its integrity and function during natural hazard events.

11.3.5 General risk management approach

For natural hazards and/or areas not addressed by policies 11.3.1, 11.3.2, and 11.3.3, subdivision, use or development of land shall be avoided if the risk from natural hazards is unacceptable. When determining whether risk is unacceptable, the following matters will be considered:

1. the likelihood of the natural hazard event; and

2. the potential consequence of the natural hazard event for: people and communities, property and infrastructure and the environment, and the emergency response organisations.

Where there is uncertainty in the likelihood or consequences of a natural hazard event, the local authority shall adopt a precautionary approach.

Formal risk management techniques should be used, such as the Risk Management Standard (AS/NZS ISO

31000:2009) or the Structural Design Action Standard (AS/NZS 1170.0:2002).

11.3.6 Role of natural features

The role of natural topographic (or geographic) and vegetation features which assist in avoiding or mitigating natural hazards should be recognised and the features maintained, protected and restored, where appropriate.

11.3.7 Physical mitigation works

New physical works to mitigate natural hazards will be acceptable only where:

1. the natural hazard risk cannot reasonably be avoided; and

2. any adverse effects of those works on the natural and built environment and on the cultural values of Ngāi Tahu, are avoided, remedied or mitigated.

Alternatives to physical works, such as the relocation, removal or abandonment of existing structures should be considered.

Where physical mitigation works or structures are developed or maintained by local authorities, impediments to accessing those structures for maintenance purposes will be avoided.

11.3.8 Climate change

When considering natural hazards, and in determining if new subdivison, use or development is appropriate and sustainable in relation to the potential risks from natural hazard events, local authorities shall have particular regard to the effects of climate change.

11.3.9 Integrated management of, and preparedness for, natural hazards

To undertake natural hazard management and preparedness for natural hazard events in a coordinated and

integrated manner by ensuring that the lead agencies have particular regard to:

1. the investigation and identification of natural hazards;

2. the analysis and mapping of the consequential effects of the natural hazards identified;

3. the effects of climate change and resulting sea level rise;

4. the setting of standards and guidelines for organisations involved in civil defence and emergency

management;

5. the development and communication of strategies to promote and build community resilience; and

6. any other matters necessary to ensure the integrated management of natural hazards in the

Canterbury region.

11.3.9 Integrated management of, and preparedness for, natural hazards

To undertake natural hazard management and preparedness for natural hazard events in a coordinated and integrated manner by ensuring that the lead agencies have particular regard to:

1. the investigation and identification of natural hazards;

2. the analysis and mapping of the consequential effects of the natural hazards identified;

3. the effects of climate change and resulting sea level rise;

4. the setting of standards and guidelines for organisations involved in civil defence and emergency management;

5. the development and communication of strategies to promote and build community resilience; and

6. any other matters necessary to ensure the integrated management of natural hazards in the Canterbury region.

Objectives and Policies, New Zealand Coastal Policy Statement

Policy 24 Identification of coastal hazards

(1) Identify areas in the coastal environment that are potentially affected by coastal hazards (including tsunami), giving priority to the identification of areas at high risk of being affected. Hazard risks, over at least 100 years, are to be assessed having regard to:

(a) physical drivers and processes that cause coastal change including sea level rise;

(b) short-term and long-term natural dynamic fluctuations of erosion and accretion;

(c) geomorphological character;

(d) the potential for inundation of the coastal environment, taking into account potential sources, inundation pathways and overland extent;

(e) cumulative effects of sea level rise, storm surge and wave height under storm conditions;

(f) influences that humans have had or are having on the coast;

(g) the extent and permanence of built development; and

(h) the effects of climate change on:

(i) matters (a) to (g) above;

(ii) storm frequency, intensity and surges; and

(iii) coastal sediment dynamics;

taking into account national guidance and the best available information on the likely effects of climate change on the region or district.

Policy 25 Subdivision, use, and development in areas of coastal hazard risk

In areas potentially affected by coastal hazards over at least the next 100 years:

(a) avoid increasing the risk10 of social, environmental and economic harm from coastal hazards;

(b) avoid redevelopment, or change in land use, that would increase the risk of adverse effects from coastal hazards;

(c) encourage redevelopment, or change in land use, where that would reduce the risk of adverse effects from coastal hazards, including managed retreat by relocation or removal of existing structures or their abandonment in extreme circumstances, and designing for relocatability or recoverability from hazard events;

(d) encourage the location of infrastructure away from areas of hazard risk where practicable;

(e) discourage hard protection structures and promote the use of alternatives to them, including natural defences; and

(f) consider the potential effects of tsunami and how to avoid or mitigate them.

Policy 26 Natural defences against coastal hazards

(1) Provide where appropriate for the protection, restoration or enhancement of natural defences that protect coastal land uses, or sites of significant biodiversity, cultural or historic heritage or geological value, from coastal hazards.

(2) Recognise that such natural defences include beaches, estuaries, wetlands, intertidal areas, coastal vegetation, dunes and barrier islands.

Policy 27 Strategies for protecting significant existing development from coastal hazard risk

(1) In areas of significant existing development likely to be affected by coastal hazards, the range of options for reducing coastal hazard risk that should be assessed includes:

(a) promoting and identifying long-term sustainable risk reduction approaches including the relocation or removal of existing development or structures at risk;

(b) identifying the consequences of potential strategic options relative to the option of ‘do-nothing’;

(c) recognising that hard protection structures may be the only practical means to protect existing infrastructure of national or regional importance, to sustain the potential of built physical resources to meet the reasonably foreseeable needs of future generations;

(d) recognising and considering the environmental and social costs of permitting hard protection structures to protect private property; and

(e) identifying and planning for transition mechanisms and timeframes for moving to more sustainable approaches.

(2) In evaluating options under (1):

(a) focus on approaches to risk management that reduce the need for hard protection structures and similar engineering interventions;

(b) take into account the nature of the coastal hazard risk and how it might change over at least a 100-year timeframe, including the expected effects of climate change; and

(c) evaluate the likely costs and benefits of any proposed coastal hazard risk reduction options.

(3) Where hard protection structures are considered to be necessary, ensure that the form and location of any structures are designed to minimise adverse effects on the coastal environment.

(4) Hard protection structures, where considered necessary to protect private assets, should not be located on public land if there is no significant public or environmental benefit in doing so.

SCIRT Projects information

#11076 Aranui Knights Drain (SW) - construction of new infrastructure including a new stormwater pump station with a pressure main and outfall discharging to the Avon River, required to alleviate stormwater flooding in the Knights Drain catchment, located in Aranui. The peak inflow into the pond in the 2% AEP design event is about 800 L/s. The selected pump station has a capacity of 450 L/s with one pump operating, and 675 L/s with both operating.

#11070 Blake St New Stormwater PS – The 1000 L/s capacity stormwater pump station is designed to support the gravity stormwater system during high tides and large rainfall events. A DN1200 gravity outfall at the end of Kibblewhite Street discharges flows up to a 5-year Annual Recurrence Interval (ARI). The outfall relies on a 2000 m^3 retention basin to store flows during high tides when it is not possible to discharge the full flow to the Avon River. During longer duration rainfall events that exceed the storage capacity of the pond, the pump station will pump the stormwater directly to the river. Hydraulic modelling calculates that if the pump station fails to operate, the lowest house will flood in 4.5 hours under the design rainfall event of a 50-year ARI rainfall event with a 6-hour duration which coincides with a 5-year ARI high tide.

#11110 New Brighton (Includes PS0230 & PS0231) - A pumped stormwater solution is required to drain the work package area when tide levels rise above approximately 10.2 m RL. Post-earthquake modelling was completed to assess the flooding in a 5 year storm with 1 year tide, and 50 year storm with 5 year tide. Following refinement of the model, two pump stations (at Beresford Street and Owles Terrace) operating at 800 l/s are required within the northern part of the catchment. Horizontal axial flow flood pumps have been specified. Backflow protection has been included at outfalls.

#11238 New Brighton Rd, Do Min - SCIRT was instructed through CRF:CERA-SCT#0344 to develop an interim design using temporary stop banks that provides a 5 year design life, while wider flood protection options/measures are developed by CCC. The intent of this project is to undertake the work necessary to reduce the roughness at isolated locations, reduce the extent of the tidal flooding, and provide a footpath to a gritted footpath standard where required. This project will improve the level of service until the future of the stop banks and network strategy is confirmed by CCC, and will reduce ongoing maintenance costs during that period. The design philosophy is to maintain 2 lanes of dry carriageway for a rainfall event with a two year probability. This approach allows for ponding in the swale system if the rainfall coincided with a high tide and then the water would drain via the existing SW outlets when the river level drops sufficiently to allow the non-return valves to open.

#11101 PS205 New Brighton Rd - Pump Station 205 is a 13 m^3/s stormwater pump station located on Horseshoe Lake, Burwood. The pump station uses three Archimedes screws to lift stormwater from Horseshoe Lake to the Avon River. The mechanical equipment is housed in a concrete building that is founded on a large number of concrete piles. The facility performed remarkably well during the earthquakes and suffered only minor structural damage and no mechanical damage. The land surrounding the pump station suffered extensive damage from liquefaction and settled by as much as 400-600 mm. The piled foundations of the pump station limited settlement of the structure to approximately 200 mm with a small amount of differential settlement (50 mm differential settlement ±15 mm). SCIRT has carried out minimal repairs to keep the pump station operating.

#11027 Main Road Causeway Stage 2 – Seawall Renewal - The Seawall on the northern side of Main Road across the McCormacks Bay Causeway has been damaged by earthquakes. This section of seawall is 980m and has been widened to accommodate a 1.5m service/drainage strip and a 4m shared coastal pathway. The full length of the seawall has been built with a crest height of 11.20m, with rip rap on a 1V:2H slope. The shoulder width beyond the edge of seal to the top of the new seawall is 6.4m.

The rock revetment has a design life of 100 years. The rock revetment has been designed for a 1% Annual Exceedance Probability wave event. The significant wave height (H_s) used in the design is 0.45m. This is combined with an assumed water level of 10.7m above Christchurch Drainage Datum (CDD) datum. The expected overtopping quantity of the rock revetment has been calculated as 0.38 l/m/s, which under the design event exceeds the allowable overtopping quantities set by CCC. However, this overtopping volume is very low and unlikely to cause any serious problems with pedestrians. The allowable damage on the revetment wall is 5% under the design event. Under normal conditions the rock revetment will require maintenance, generally by the addition of new rock of equivalent size and quantity to the existing structure.

The Tsunami Study undertaken by NIWA was considered in the revetment design, which modelled the worst case scenario for Canterbury, the 1868 South American tsunami.

In the event of a tsunami, the sea level in the Heathcote Estuary may rise above the crest height of the designed rock revetment. Damage of the revetment may occur as a result of fast flowing water and debris. However the probability of this is considered to be lower than the design event. The principal impact of climate change is expected to be an increase in overtopping frequency and amount, as sea levels rise. CCC has adopted a long term high water level of 10.7m above CDD. This allows for storm surge (0.3m) and minimal allowance for future sea level rise (0.05m) above MHWS. As the revetment is a permeable structure, flooding of the land behind the revetment may still occur as a consequence of potential increase in water levels.

#11200 Beachville - A rock revetment will replace the existing vertical concrete seawall along the Avon Heathcote Estuary, adjacent to Beachville Road in Christchurch. The concrete seawall was damaged in the earthquakes and sections of the wall have collapsed. The seawall is to be replaced by a rock revetment. This section of the revetment is approximately 500m long. CCC has adopted a long term high water level of 10.7m above CDD. This allows for storm surge (0.3m) and minimal allowance for future sea

level rise (0.05m) above MHWS. The extreme water level in the Avon Heathcote Estuary is 10.942m at a 100 year ARI (water levels have been predicted by Derek Goring). This value is 0.15m greater than MHWS and Storm Surge value of 10.79m (10.49m+0.3m).

Table 4: Design Criteria for Main Road Causeway and Beachville Road

Item	Main Road Causeway Criteria	Beachville Road Criteria
Design Life	100 years	100 years
Design Event (Annual Recurrence Interval)	1 in 100 years	1 in 100 years
Damage under design Conditions	5%	5%
Design Crest Height	**11.2m**	**11.4m**
Overtopping	Range of 0.01 to 0.1l/s/m is acceptable	Range of 0.01 to 0.1l/s/m is acceptable
Slope of Face	1 in 2	1 in 2

The only difference in the design criteria for Main Road Causeway and Beachville Road as selected by Christchurch City Council is the design crest height at each site, shown in bold above.

#11118 NZTA Travis Rd Repairs – *Bruce Steven stated that this road has been raised 400 mm.* Earthquake repairs to the NZTA's SH74 Travis Road from the Burwood Road intersection to Corsers

Stream culvert and the new intersection layout at Travis Road and Bassett Street. This represents a length of 1.34 km. Earthquake damage suffered in the area was extensive due to the close proximity to the Travis Wetland and Liquefaction Zone where ground conditions are subject to lateral spread and/or differential settlement. The Travis Road Bassett Street Intersection Improvement design has been incorporated into the repair works. The roading repair scope has been reviewed in accordance with Network Guideline DG36A. Roading restoration includes both carriageway and kerbing, following further site inspections and review of pre and post-earthquake cross sectional shape and longitudinal gradients. Generally longitudinal grade has been lost and, where this corresponds to ponding issues and RAMM repairs, the design has restored grades to a minimum of 1 in 500. The length of carriageway being reconstructed is 700 m. Where necessary, new stormwater sumps and pipes are required to provide minimum gradients and to minimise the extent of drainage related new pavement construction.

#11118 NZTA SH74 Travis Rd Repairs - Dyers Road forms part of State Highway 74, a strategic freight route heading north from the Port of Lyttelton, through the eastern suburbs of Christchurch to Belfast, where it connects to State Highway 1. It carries approximately 15,500 vpd with a heavy vehicle proportion of 5.5% (State Highway Traffic Data Booklet 2007-2011, NZTA website). This section of Dyers Road suffered extensive longitudinal cracking in the carriageway caused by lateral spreading and differential settlement, resulting in an undulating longitudinal profile with poor quality of ride and drainage issues with water pooling along the shoulders. Areas outside of the pond embankments have minor damage only. Changes to the vertical geometry along the centreline and road shoulders were made to correct the undulating vertical profile and to allow water to freely drain again to the edge of the road.